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**PRELIMINARY HANDLING QUALITIES REQUIREMENTS
FOR LIFTING RE-ENTRY VEHICLES
DURING TERMINAL FLIGHT**

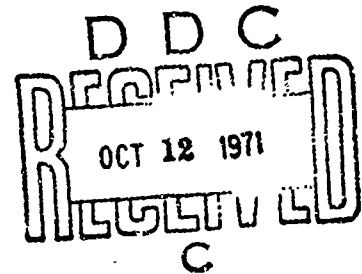
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CORNELL AERONAUTICAL LABORATORY, INC.

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**PRELIMINARY HANDLING QUALITIES REQUIREMENTS
FOR LIFTING RE-ENTRY VEHICLES
DURING TERMINAL FLIGHT**

DANTE A. DI FRANCO

JOHN F. MITCHELL

CORNELL AERONAUTICAL LABORATORY, INC.

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FOREWORD

This preliminary draft of handling qualities requirements for lifting re-entry vehicles during terminal flight was prepared for the United States Air Force by Cornell Aeronautical Laboratory, Inc., Buffalo, New York in partial fulfillment of Project 680A, Contract F33615-70-C-1755. This report covers work performed during the period from July 1970 through June 1971.

The investigations under this contract were performed by the Flight Research Department of Cornell Aeronautical Laboratory (CAL) under sponsorship of the Air Force Flight Dynamics Laboratory (AFFDL), Wright-Patterson Air Force Base, Ohio. Mr. James Pruner and Terry Neighbor (AFFDL/FGC) were project engineers for the Flight Dynamics Laboratory.

Project engineer for CAL was Mr. D.A. DiFranco. Mr. DiFranco and Mr. J.F. Mitchell were principal investigators throughout the project. Some valuable contributions were made by Robert Radford. The investigation was under the general supervision of Mr. C.R. Chalk, whose comments were of invaluable assistance. He also participated in handling qualities review meetings and reviewed the final report.

As part of this investigation, handling qualities review meetings were held with some of the interested contractors and government agencies. The assistance of all of those who participated in these discussions is gratefully acknowledged. Their comments, suggestions, and information that they supplied were of assistance in preparing this preliminary draft of handling qualities requirements. The contractors and government agencies visited are listed below:

1. NASA/Marshall Space Flight Center
2. Lockheed Georgia Company
3. NASA/Manned Spacecraft Center
4. Martin Marietta Corporation/Denver Division
5. McDonnell-Douglas Astronautics Corporation, East
6. NASA/Ames Research Center
7. General Dynamics/Convair Aerospace
8. North American Rockwell/Los Angeles Division
9. NASA/Flight Research Center
10. Air Force Flight Test Center.

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This technical report has been reviewed and is approved.



C.B. WESTBROOK

Chief, Control Criteria Branch
Flight Control Division
Air Force Flight Dynamics Laboratory

ABSTRACT

Preliminary handling qualities requirements for lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds are presented and discussed. Included are a preliminary draft of a flying qualities specification for piloted re-entry vehicles and the rationale and backup data upon which the flying qualities requirements are based. Many of the requirements were adapted from, or are similar to, the requirements for piloted airplanes presented in the latest revision of the flying qualities specification for military airplanes, MIL-F-8785B(ASG). Some requirements that are new and unique to lifting re-entry vehicles have been added. The format of the specification is similar to that of MIL-F-8785B(ASG), therefore, comparison of flying qualities requirements of lifting re-entry vehicles and airplanes is facilitated. These flying qualities requirements are preliminary and subject to revisions based on future research and additional discussions with interested contractors and government agencies.

TABLE OF CONTENTS

Section		Page
I	INTRODUCTION.	1
II	PRELIMINARY SPECIFICATION FOR THE FLYING QUALITIES OF PILOTED RE-ENTRY VEHICLES DURING TERMINAL FLIGHT.	8
	1. SCOPE AND CLASSIFICATIONS	8
	1.1 Scope	8
	1.2 Application	8
	1.3 Classification of vehicles.	8
	1.3.1 Operational or experimental designation.	8
	1.4 Flight Phase Categories	8
	1.5 Levels of flying qualities.	10
	2. APPLICABLE DOCUMENTS.	10
	3. REQUIREMENTS	11
	3.1 General requirements.	11
	3.1.1 Missions	11
	3.1.2 Loadings	11
	3.1.3 Moments of inertia	11
	3.1.4 External stores.	11
	3.1.5 Configurations	12
	3.1.6 State of the vehicle	12
	3.1.6.1 Vehicle Normal States	12
	3.1.6.2 Vehicle Failure States.	12
	3.1.6.2.1 Vehicle Special Failure States	13
	3.1.7 Operational Flight Envelopes	13
	3.1.8 Service Flight Envelopes	13
	3.1.8.1 Maximum service speed	13
	3.1.8.2 Minimum service speed	14
	3.1.8.3 Maximum service altitude	15
	3.1.8.4 Service load factors.	16

TABLE OF CONTENTS (Cont)

<u>Section</u>		<u>Page</u>
II	3.1.9 Permissible Flight Envelopes.	16
	3.1.9.1 Maximum permissible speed (minimum permissible angle of angle).	16
	3.1.9.2 Minimum permissible speed (maximum permissible angle of attack)	16
	3.1.9.2.1 Minimum permissible speed (maximum permissible angle of attack) based on other considerations. . .	17
	3.1.10 Application of Levels	17
	3.1.10.1 Requirements for Vehicle Normal States	17
	3.1.10.2 Requirements for Vehicle Failure States	17
	3.1.10.2.1 Requirements on the effects of specific failures	18
	3.1.10.3 Exceptions	19
	3.1.10.3.1 Ground operation and Terminal Flight Phases. .	19
	3.1.10.3.2 When Levels are not specified	19
	3.1.10.3.3 Flight outside the Service Flight Envelope	19
3.2	Longitudinal flying qualities	19
	3.2.1 Longitudinal stability with respect to speed. .	19
	3.2.1.1 Longitudinal trim stability.	19
	3.2.1.1.1 Relaxation in transonic flight.	20

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
II	
3.2.1.1.2 Elevator control force variations during rapid speed or Mach number changes	21
3.2.1.1.3 Elevator control force variations during angle of attack transitions . .	21
3.2.1.2 Phugoid stability.	21
3.2.1.3 Flight-path stability.	21
3.2.2 Longitudinal maneuvering characteristics. . .	22
3.2.2.1 Short-period response.	22
3.2.2.1.1 Short-period frequency and acceleration sensitivity	23
3.2.2.1.2 Short-period damping. . .	23
3.2.2.1.3 Residual oscillations . .	26
3.2.2.2 Control feel and control motion in maneuvering flight	26
3.2.2.2.1 Control forces in maneuvering flight. . . .	26
3.2.2.2.2 Control motions in maneuvering flight. . . .	26
3.2.2.3 Longitudinal pilot-induced oscillations	26
3.2.2.3.1 Transient control forces	28
3.2.3 Longitudinal control	28
3.2.3.1 Longitudinal control in unaccelerated flight	28
3.2.3.2 Longitudinal control in maneuvering flight	26
3.2.3.3 Longitudinal control in takeoff	28

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
II	
3.2.3.3.1 Longitudinal control during air launch	28
3.2.3.3.2 Longitudinal control force and travel in takeoff and during air launch	29
3.2.3.4 Longitudinal control in landing. . .	29
3.2.3.4.1 Longitudinal control forces in landing	29
3.2.3.4.2 Power-off and unpowered longitudinal control requirements in landing .	30
3.2.3.4.3 Elevator lift and longitudinal control in landing	31
3.2.3.5 Longitudinal control forces in dives - Service Flight Envelope. . .	31
3.2.3.6 Longitudinal control forces in dives - Permissible Flight Envelope. .	32
3.2.3.7 Longitudinal control in sideslips. .	32
3.3 Lateral-directional flying qualities	32
3.3.1 Lateral-directional mode characteristics. . .	32
3.3.1.1 Lateral-directional oscillations (Dutch roll)	32
3.3.1.1.1 Directional control margin.	33
3.3.1.2 Roll mode	33
3.3.1.3 Spiral stability	34
3.3.1.4 Coupled roll-spiral oscillation. . .	34
3.3.2 Lateral-directional dynamic response characteristics	35
3.3.2.1 Lateral-directional response to atmospheric disturbances	35
3.3.2.2 Roll rate oscillations	35

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
II	
3.3.2.2.1 Additional roll rate requirements for small inputs	36
3.3.2.3 Bank angle oscillations	36
3.3.2.4 Sideslip excursions	37
3.3.2.4.1 Additional sideslip requirements for small inputs	37
3.3.2.5 Control of sideslip in rolls.	38
3.3.2.6 Turn coordination	38
3.3.3 Pilot-induced oscillations	39
3.3.4 Roll control effectiveness	39
3.3.4.1 Roll response to aileron control force	39
3.3.4.2 Aileron control forces.	40
3.3.4.3 Linearity of roll response.	40
3.3.4.4 Wheel control throw	40
3.3.4.5 Rudder-pedal-induced rolls.	41
3.3.5 Directional control characteristics.	41
3.3.5.1 Directional control with speed change.	41
3.3.5.1.1 Directional control with asymmetric loading	41
3.3.5.2 Directional control in go-around.	41
3.3.6 Lateral-directional characteristics in steady sideslips	41
3.3.6.1 Yawing moments in steady sideslips.	42
3.3.6.2 Side forces in steady sideslips	42
3.3.6.3 Rolling moments in steady sideslips	42
3.3.6.3.1 Exception for go-around.	42
3.3.6.3.2 Positive effective dihedral limit	42

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
II	
3.3.7 Lateral-directional control in crosswinds	43
3.3.7.1 Final approach in crosswinds.	43
3.3.7.2 Takeoff run and landing rollout in crosswinds	43
3.3.7.2.1 Cold- and wet-weather operation.	43
3.3.7.3 Taxiing wind speed limits	44
3.3.8 Lateral-directional control in dives	44
3.3.9 Lateral-directional control with asymmetric thrust	44
3.3.9.1 Thrust loss during takeoff run.	44
3.3.9.2 Thrust loss after takeoff	44
3.3.9.3 Transient effects	45
3.3.9.4 Asymmetric thrust - rudder pedals free.	45
3.3.9.5 Two engines inoperative	45
3.4 Miscellaneous requirements.	45
3.4.1 Approach to dangerous flight conditions.	45
3.4.1.1 Warning and indication.	45
3.4.1.2 Prevention	45
3.4.2 Stalls	46
3.4.2.1 Required conditions	46
3.4.2.2 Stall warning requirements.	46
3.4.2.2.1 Warning speed for stalls at $1g \cos \theta$ normal to the flight path	46
3.4.2.2.2 Warning range for accelerated stalls	46
3.4.2.3 Stall characteristics	47
3.4.2.4 Stall recovery and prevention	47
3.4.2.4.1 One-engine-out stalls.	47

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
ii	
3.4.3 Spin recovery.	48
3.4.4 Roll-pitch-yaw coupling.	48
3.4.5 Control harmony.	48
3.4.5.1 Control force coordination.	48
3.4.6 Buffet	48
3.4.7 Release of stores.	48
3.4.8 Effects of special equipment	48
3.4.9 Transients following failures.	49
3.4.10 Failures	49
3.5 Characteristics of the primary flight control system.	49
3.5.1 General characteristics.	49
3.5.2 Mechanical characteristics	49
3.5.2.1 Control centering and breakout forces	49
3.5.2.2 Cockpit control free play	49
3.5.2.3 Rate of control displacement.	50
3.5.2.4 Adjustable controls	50
3.5.3 Dynamic characteristics	50
3.5.3.1 Control feel	51
3.5.3.2 Damping	51
3.5.4 Augmentation systems	51
3.5.4.1 Performance of augmentation systems	51
3.5.4.2 Saturation of augmentation systems	51
3.5.5 Failures	51
3.5.5.1 Failure transients.	51
3.5.5.2 Trim changes due to failures.	52
3.5.6 Transfer to alternate control modes.	52
3.5.6.1 Transients.	52
3.5.6.2 Trim changes.	52

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
II 3.6 Characteristics of secondary control systems.	53
3.6.1 Trim system.	53
3.6.1.1 Trim for asymmetric thrust.	53
3.6.1.2 Rate of trim operation.	53
3.6.1.3 Stalling of trim systems.	53
3.6.1.4 Trim system irreversibility	53
3.6.2 Speed and flight-path control devices.	54
3.6.3 Transient and trim changes	54
3.6.3.1 Pitch trim changes.	54
3.6.4 Auxiliary dive recovery devices.	54
3.6.5 Direct normal-force control.	55
3.7 Atmospheric disturbances.	55
3.7.1 Use of turbulence models	55
3.7.2 Turbulence models.	55
3.7.2.1 Continuous random model (von Karman form)	55
3.7.2.2 Continuous random model (Dryden form)	55
3.7.2.3 Non-Gaussian models (von Karman or Dryden form).	56
3.7.2.4 Discrete model.	56
3.7.3 Scales and intensities (clear air turbulence).	57
3.7.3.1 Clear air turbulence (von Karman scales)	57
3.7.3.2 Clear air turbulence (Dryden scales)	57
3.7.4 Scales and intensities (thunderstorm turbulence)	59
3.7.4.1 Thunderstorm turbulence (von Karman scales)	59
3.7.4.2 Thunderstorm turbulence (Dryden scales)	59

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
II	
3.7.5 Application of the turbulence models in analysis	59
4. QUALITY ASSURANCE	60
4.1 Compliance demonstration.	60
4.2 Vehicle states.	61
4.2.1 Weights and moments of inertia	61
4.2.2 Center-of-gravity positions.	61
4.2.3 Thrust settings.	61
4.3 Design and test conditions.	61
4.3.1 Altitudes.	61
4.3.2 Special conditions	62
4.4 Interpretation of qualitative requirements.	62
5. PREPARATION FOR DELIVERY.	62
5.1 General	62
6. NOTES	62
6.1 Intended use.	62
6.2 Definitions	62
6.2.1 General.	63
6.2.2 Speeds	63
6.2.3 Thrust and boost	65
6.2.4 Control parameters	65
6.2.5 Longitudinal parameters.	66
6.2.6 Lateral-directional parameters	68
6.2.7 Atmospheric disturbances parameters.	74
6.3 Interpretation of the F_s/n limits of table V	75
6.4 Gain scheduling	75
6.5 Engine considerations	75
6.6 Effects of aeroelasticity, control equipment, and structural dynamics	75
6.7 Application of levels	77

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
6.7.1 Theoretical compliance	77
6.7.2 Level definitions	78
6.7.3 Computational assumptions.	78
6.8 Related documents	79
III FLYING QUALITIES RATIONALE	82
1. SCOPE AND CLASSIFICATIONS	82
1.1 Scope	82
1.2 Application	82
1.3 Classification of vehicles.	82
1.3.1 Operational or experimental designation.	82
1.4 Flight Phase Categories	94
1.5 Levels of flying qualities.	97
2. APPLICABLE DOCUMENTS.	98
3. REQUIREMENTS	98
3.1 General requirements.	98
3.1.1 Missions	98
3.1.2 Loadings	98
3.1.3 Moments of inertia	98
3.1.4 External stores.	98
3.1.5 Configurations	98
3.1.6 State of the vehicle	99
3.1.6.1 Vehicle Normal States	99
3.1.6.2 Vehicle Failure States	99
3.1.6.2.1 Vehicle Special Failure States	99
3.1.7 Operational Flight Envelopes	100
3.1.8 Service Flight Envelopes	100
3.1.8.1 Maximum service speed	100
3.1.8.2 Minimum service speed	100

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
III	
3.1.8.3 Maximum service altitude.	100
3.1.8.4 Service load factors.	100
3.1.9 Permissible Flight Envelopes	102
3.1.9.1 Maximum permissible speed (minimum permissible angle of attack).	102
3.1.9.2 Minimum permissible speed (maximum permissible angle of attack).	102
3.1.9.2.1 Minimum permissible speed (maximum permissible angle of attack) based on other considerations	102
3.1.10 Application of Levels	103
3.1.10.1 Requirements for Vehicle Normal States	103
3.1.10.2 Requirements for Vehicle Failure States	103
3.1.10.2.1 Requirements on the effects of specific failures	103
3.1.10.3 Exceptions.	103
3.1.10.3.1 Ground operation and Terminal Flight Phases	103
3.1.10.3.2 When Levels are not specified	103
3.1.10.3.3 Flight outside the Service Flight Envelope.	103
3.2 Longitudinal flying qualities	105
3.2.1 Longitudinal stability with respect to speed .	105
3.2.1.1 Longitudinal trim stability	105
3.2.1.1.1 Relaxation in transonic flight	107

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
III	
3.2.1.1.2 Elevator control force variations during rapid speed or Mach number changes	107
3.2.1.1.3 Elevator control force variations during angle of attack transitions. . .	107
3.2.1.2 Phugoid stability	107
3.2.1.3 Flight-path stability	107
3.2.2 Longitudinal maneuvering characteristics . . .	111
3.2.2.1 Short-period response	111
3.2.2.1.1 Short-period frequency and acceleration sensitivity .	111
3.2.2.1.2 Short-period damping . . .	111
3.2.2.1.3 Residual oscillations. . .	117
3.2.2.2 Control feel and control motion in maneuvering flight.	122
3.2.2.2.1 Control forces in maneuvering flight	122
3.2.2.2.2 Control motions in maneuvering flight	122
3.2.2.3 Longitudinal pilot-induced oscillations	124
3.2.2.3.1 Transient control forces	124
3.2.3 Longitudinal control	125
3.2.3.1 Longitudinal control in unaccelerated flight	125
3.2.3.2 Longitudinal control in maneuvering flight	125
3.2.3.3 Longitudinal control in takeoff . . .	127

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
III	
3.2.3.3.1 Longitudinal control during air launch.	127
3.2.3.3.2 Longitudinal control force and travel in takeoff and during air launch	127
3.2.3.4 Longitudinal control in landing	127
3.2.3.4.1 Longitudinal control forces in landing	127
3.2.3.4.2 Power-off and unpowered longitudinal control requirements in landing.	129
3.2.3.4.3 Elevator lift and longitudinal control in landing.	154
3.2.3.5 Longitudinal control forces in dives - Service Flight Envelope	157
3.2.3.6 Longitudinal control forces in dives - Permissible Flight Envelope.	157
3.2.3.7 Longitudinal control in sideslips	157
3.3 Lateral-directional flying qualities	158
3.3.1 Lateral-directional mode characteristics	158
3.3.1.1 Lateral-directional oscillations (Dutch roll)	158
3.3.1.1.1 Directional control margin	158
3.3.1.2 Roll mode	160
3.3.1.3 Spiral stability	160
3.3.1.4 Coupled roll-spiral oscillation	161
3.3.2 Lateral-directional dynamic response characteristics	162
3.3.2.1 Lateral-directional response to atmospheric disturbances.	162

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
III	
3.3.2.2 Roll rate oscillations.	163
3.3.2.2.1 Additional roll rate requirements for small inputs	163
3.3.2.3 Bank angle oscillations	164
3.3.2.4 Sideslip excursions	165
3.3.2.4.1 Additional sideslip requirements for small inputs	165
3.3.2.5 Control of sideslip in rolls	168
3.3.2.6 Turn coordination	168
3.3.3 Pilot-induced oscillations	168
3.3.4 Roll control effectiveness	168
3.3.4.1 Roll response to aileron control force	172
3.3.4.2 Aileron control forces	172
3.3.4.3 Linearity of roll response.	173
3.3.4.4 Wheel control throw	173
3.3.4.5 Rudder-pedal-induced rolls.	173
3.3.5 Directional control characteristics.	174
3.3.5.1 Directional control with speed change.	174
3.3.5.1.1 Directional control with asymmetric loading	175
3.3.5.2 Directional control in go-around.	175
3.3.6 Lateral-directional characteristics in steady sideslips	175
3.3.6.1 Yawing moments in steady sideslips.	176
3.3.6.2 Side forces in steady sideslips	177
3.3.6.3 Rolling moments in steady sideslips	177

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
III	
3.3.6.3.1 Exception for go-around.	178
3.3.6.3.2 Positive effective dihedral limit	178
3.3.7 Lateral-directional control in crosswinds. . .	179
3.3.7.1 Final approach in crosswinds.	179
3.3.7.2 Takeoff run and landing rollout in crosswinds.	180
3.3.7.2.1 Cold- and wet-weather operation.	180
3.3.7.3 Taxiing wind speed limits	181
3.3.8 Lateral-directional control in dives	181
3.3.9 Lateral-directional control with asymmetric thrust	181
3.3.9.1 Thrust loss during takeoff run.	181
3.3.9.2 Thrust loss after takeoff	182
3.3.9.3 Transient effects	183
3.3.9.4 Asymmetric thrust - rudder pedals free	183
3.3.9.5 Two engines inoperative	184
3.4 Miscellaneous requirements	184
3.4.1 Approach to dangerous flight conditions. . . .	184
3.4.1.1 Warning and indication.	184
3.4.1.2 Prevention	184
3.4.2 Stalls	185
3.4.2.1 Required conditions	185
3.4.2.2 Stall warning requirements.	185
3.4.2.2.1 Warning speed for stalls at $lg \cos \gamma$ normal to the flight path.	185
3.4.2.2.2 Warning range for accelerated stalls	185

TABLE OF CONTENTS (Cont)

Section	Page
1.1	
3.4.2.3 Stall characteristics	185
3.4.2.4 Stall recovery and prevention	185
3.4.2.4.1 One-engine-out stalls.	185
3.4.3 Spin recovery	185
3.4.4 Roll-pitch-yaw coupling.	185
3.4.5 Control harmony.	186
3.4.5.1 Control force coordination.	186
3.4.6 Buffet	186
3.4.7 Release of stores	186
3.4.8 Effects of special equipment	186
3.4.9 Transients following failures.	186
3.4.10 Failures	186
3.5 Characteristics of the primary flight control system	187
3.5.1 General characteristics	187
3.5.2 Mechanical characteristics	187
3.5.2.1 Control centering and breakout forces.	187
3.5.2.2 Cockpit control free play	187
3.5.2.3 Rate of control displacement.	187
3.5.2.4 Adjustable controls	187
3.5.3 Dynamic characteristics	187
3.5.3.1 Control feel	187
3.5.3.2 Damping	187
3.5.4 Augmentation systems	188
3.5.4.1 Performance of augmentation systems	189
3.5.4.2 Saturation of augmentation systems	189
3.5.5 Failures	190

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
III	
3.5.5.1 Failure transients.	190
3.5.5.2 Trim changes due to failures.	190
3.5.6 Transfer to alternate control modes	190
3.5.6.1 Transients	190
3.5.6.2 Trim changes	190
3.6 Characteristics of secondary control systems.	190
3.6.1 Trim system.	190
3.6.1.1 Trim for asymmetric thrust.	191
3.6.1.2 Rate of trim operation.	191
3.6.1.3 Stalling of trim systems.	191
3.6.1.4 Trim system irreversibility	191
3.6.2 Speed and flight-path control devices.	191
3.6.3 Transient and trim changes	192
3.6.3.1 Pitch trim changes.	192
3.6.4 Auxiliary dive recovery devices.	192
3.6.5 Direct normal-force control.	192
3.7 Atmospheric disturbances.	192
3.7.1 Use of turbulence models	192
3.7.2 Turbulence models.	192
3.7.2.1 Continuous random model (von Karman form)	192
3.7.2.2 Continuous random model (Dryden form)	192
3.7.2.3 Non-Gaussian models (von Karman or Dryden form)	192
3.7.2.4 Discrete model.	192
3.7.3 Scales and intensities (clear air turbulence).	194
3.7.3.1 Clear air turbulence (von Karman scales)	194
3.7.3.2 Clear air turbulence (Dryden scales)	194

TABLE OF CONTENTS (Cont)

<u>Section</u>	<u>Page</u>
III	
3.7.4 Scales and intensities (thunderstorm turbulence)	194
3.7.4.1 Thunderstorm turbulence (von Karman scales)	194
3.7.4.2 Thunderstorm turbulence (Dryden scales)	194
3.7.5 Application of the turbulence models in analysis	196
4. QUALITY ASSURANCE	197
4.1 Compliance demonstration	197
4.2 Vehicle states.	197
4.2.1 Weights and moments of inertia	197
4.2.2 Center-of-gravity positions.	197
4.2.3 Thrust settings.	197
4.3 Design and test conditions.	197
4.3.1 Altitudes.	197
4.3.2 Special conditions	197
4.4 Interpretation of qualitative requirements.	197
REFERENCES	200

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Short Period Frequency Requirements - Class IV.	24
2	Short Period Frequency Requirements - Class III	25
3	Flare Altitude and Flare Time for Unpowered Landings (Classes III(E) and IV(E))	31
4	Roll Rate Oscillation Limitations	36
5	Bank Angle Oscillation Limitations	37
6	Sideslip Excursion Limitations	38
7	Magnitude of Discrete Gusts	58
8	Intensity for Clear Air Turbulence	58
9	Roll-Sideslip Coupling Parameters - Right Rolls	72
10	Roll-sideslip Coupling Parameters - Left Rolls.	73
11	Elevator Maneuvering Force Gradient Limits: Center-Stick Controller, $\eta_L = 4.0$	75
12	Comparison of M2-F2, HL-10 and X-24A Flight Test Results to Class IV Short-Period Frequency Requirements.	115
13	Comparison of HL-10 Shuttle Ground Simulation Results to Class III Short-Period Frequency Requirements	115
14	Ground Test Set-up	119
15	X-24A Pitch Limit-Cycle Characteristics	119
16	Limit Cycle Acceptance Criteria	119
17	Unpowered Flare and Landing Profile (Reference 34).	132
18	Unpowered Landings C_L and (L/D) Relationships (Reference 2a). .	132
19	Landing Data on First 30 Flights of X-15 (Reference 30)	134
20	Landing Flight Path Data on First 30 Flights of X-15 (Reference 30).	135
21	Typical X-15 Flare and Landing (Reference 30)	145
22	Comparison of Flare Time and Flare Altitude of First 30 Flights of X-15 (Reference 30)	146
23	Variation of Float Time on First 30 Flights of X-15 (Reference 30).	147
24	Flares of the M2-F2 and HL-10 Vehicles	149
25	Flares of the X-24A	149

LIST OF ILLUSTRATIONS (Cont)

<u>Figure</u>		<u>Page</u>
26	Low L/D Flares of F-111A and NB-52A.	149
27	Flare Data from Simulated Low (L/D) Approaches	151
28	Float Time for Various Vehicles Performing Unpowered Landings	152
29	Composite Plot of Flare Data	152
30	Flare Altitude and Flare Time Requirements for Unpowered Landings (Class III(E) and IV(E)).	152
31	Typical Airplane Response to Abrupt Elevator Deflection (Reference 57)	156
32	Comparison of XB-70 Longitudinal Control Power with that of Subsonic Jet Transport Landing Configuration (Reference 58). .	156
33	Effect of Lift Loss on Landing Control (Reference 35).	156
34	Comparison of Probability Densities	195
35	Sketch of Turbulence Forms	195

LIST OF TABLES

<u>Table</u>		<u>Page</u>
I	Levels for Vehicle Normal States.	17
II	Levels for Vehicle Failure States	18
III	Phugoid Stability	21
IV	Short-Period Damping Ratio Limits	23
V	Elevator Maneuvering Force Gradient Limits	27
VI	Minimum and Maximum Float Time	30
VII	Minimum Dutch Roll Frequency and Damping	33
VIII	Maximum Roll Mode Time Constant	34
IX	Spiral Stability - Minimum Time to Double Amplitude	34
X	Roll Control Effectiveness.	39
XI	Maximum Aileron Control Force	40
XII	Crosswind Velocity	43
XIII	Allowable Breakout Forces, Pounds	50
XIV	Allowable Control Surface Lags	50
XV	Classification of Lifting Re-Entry Vehicles (Based on Reference 1)	85
XVI	Suggested Classification of Lifting Re-Entry Vehicles	88
XVII	Suggested Lifting Re-Entry Vehicle Classification Based on Terminal Flight at Low Supersonic, Transonic and Subsonic Speeds	93
XVIII	Suggested Lifting Re-Entry Vehicle Classifications at all Flight Speeds	95

LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

a_g	Longitudinal acceleration parallel to the flight path, g's
b	Wing span, ft
\bar{c}	Mean aerodynamic chord, ft
C_L	Lift coefficient
$(C_{L_0})_{max}$	Maximum operational lift coefficient
d_m	Generalized discrete gust length (always positive), $m = x, y, z$ (ft)
D	Aerodynamic drag, parallel to flight path, lb
F_s	Elevator control force, applied by pilot, lb
F_s/n	Gradient of steady-state elevator control force versus n at constant speed, lb/g
F_s/α	Gradient of steady-state elevator control force versus angle of attack for constant speed, lb/deg
g	Acceleration of gravity, ft/sec ²
h	Height above ground level (AGL) or above mean sea level (MSL), ft
h_f	Altitude change during flare, ft
h_{FL}	Altitude change during float, ft
h_{max}	Maximum service altitude, ft
$h_{o_{max}}$	Maximum operational altitude, ft
$h_{o_{min}}$	Minimum operational altitude, ft
I_x, I_y, I_z	Moments of inertia about x, y , and z axes, respectively, slug-ft ²
I_{xz}	Product of inertia, slug-ft ²
j	$\sqrt{-1}$

Symbols

t	Ratio of "commanded roll performance" to "applicable roll performance requirement" of 3.3.4 or 3.3.4.1, where: (a) "Applicable roll performance requirement", $(\phi_t)_{\text{requirement}}$, is determined from 3.3.4 and 3.3.4.1 for the Class, Flight Phase Category and Level under consideration. (b) "Commanded roll performance", $(\phi_t)_{\text{command}}$, is the bank angle attained in the stated time for a given step aileron command with rudder pedals employed as specified in 3.3.4 and 3.3.4.1 $t = \frac{(\phi_t)_{\text{command}}}{(\phi_t)_{\text{requirement}}}$
\bar{K}_{q_0}	Lower limit on the maximum attainable load factor, g's
$K_{h\delta_e}$	Gain constant of the altitude-elevator transfer function
K_q	Feedback gain of pitch rate to the elevator, $K_q = \delta_e / q$
$K_{u\delta_e}$	Gain constant of velocity-elevator transfer function
$K_{\gamma\delta_e}$	Gain constant of flight path-elevator transfer function
$K_{\theta\delta_e}$	Gain constant of pitch attitude-elevator transfer function
L	Aerodynamic lift plus thrust component, normal to the flight path, lb
$(L/D)_{AV,FL}$	Average lift-to-drag ratio in the float
$(L/D)_{EFF}$	Effective lift-to-drag ratio during flare
$(L/D)_{MAX}$	Maximum lift-to-drag ratio
\bar{L}	Rolling moment about the x-axis, including thrust effects, ft-lb
L_i	$= \frac{1}{I_x} \frac{\partial \bar{L}}{\partial i}$, $i = \beta, \dot{\beta}, \delta_{AS}, \delta_{RP}, p, r$
L'_i	$= \left[1 - \frac{I_{xz}^2}{I_x I_z} \right]^{-1} \left[L_i - \frac{I_{xz}}{I_x} N_i \right]$, $i = \beta, \dot{\beta}, \delta_{AS}, \delta_{RP}, p, r$
L_{α}	$= \frac{1}{mV} \frac{\partial L}{\partial \alpha}$

Symbols

L_u	Scale for u_g , ft
L_v	Scale for v_g , ft
L_w	Scale for w_g , ft
m	Mass of airplane, slugs
M	Mach number
M	Pitching moment about the y-axis, including thrust effects, ft-lb
M_i	$= \frac{1}{I_y} \frac{\partial M}{\partial i}$, $i = \alpha, \dot{\alpha}, \delta_e, \theta, \dot{\theta}, u$
n	Normal acceleration or normal load factor, measured at the c.g., g's
n/α	The steady-state normal acceleration change per unit change in angle of attack for an incremental elevator deflection at constant speed (airspeed and Mach number), g's/rad
n_g	Load factor normal to the flight path, measured at the c.g., g's
n_L	Symmetrical flight limit load factor for a given Airplane Normal State, based on structural considerations, g's
n_{max}, n_{min}	Maximum and minimum Service load factors, g's
$n(+), n(-)$	For a given altitude, the upper and lower boundaries of n in the V-n diagrams depicting the Service Flight Envelope, g's
$n_{o_{max}}, n_{o_{min}}$	Maximum and minimum Operational load factors, g's
$n_o(+), n_o(-)$	For a given altitude, the upper and lower boundaries of n_o in the V-n diagrams depicting the Operational Flight Envelope, g's
n_{δ_e}	Normal acceleration change with elevator deflection due to elevator 1 ft, g's/deg
N	Yawing moment about the z axis, including thrust effects, ft-lb
N_i	$= \frac{1}{I_z} \frac{\partial N}{\partial i}$, $i = \beta, \dot{\beta}, \delta_{AS}, \delta_{RP}, p, r$

Symbols

$$N'_i = \left[1 - \frac{I_{xz}^2}{I_x I_z} \right]^{-1} \left[N_i - \frac{I_{xz}}{I_z} L_i \right]$$

p Roll rate about the x-axis, rad/sec

p_g Rolling velocity due to random gust, rad/sec

p_n Amplitude of roll rate response at Dutch roll peaks for step aileron input, rad/sec

$\frac{p_{osc}}{p_{AV}}$ A measure of the ratio of the oscillatory component of roll rate to the average component of roll rate following a rudder-pedals-free step aileron control command

$$\xi_d \leq 0.2 : \frac{p_{osc}}{p_{AV}} = \frac{p_1 + p_3 - 2p_2}{p_1 + p_3 + 2p_2}$$

$$\xi_d > 0.2 : \frac{p_{osc}}{p_{AV}} = \frac{p_1 - p_2}{p_1 + p_2}$$

where p_1 , p_2 and p_3 are roll rates at the first, second and third peaks, respectively

$\angle \frac{p}{\beta}$ Phase angle between roll rate and sideslip in the free Dutch roll oscillation. Angle is positive when p leads β , deg

P Period of the dynamic motion, sec

\bar{q} Dynamic pressure, lb/ft²

\bar{q}_0 Operational dynamic pressure

q Pitch rate, rad/sec

q_g Pitching velocity due to random gust, rad/sec

Δq Pitch rate peak to peak amplitude, rad/sec

r Yaw rate, rad/sec

r_g Yawing velocity due to random gust, rad/sec

s Laplace transform variable, sec⁻¹

S Wing area, ft²

$SR_{AV,FL}$ Average sink rate during float, ft/sec

t Time, sec

Symbols

t_f	Flare time, time from flare initiation with $\gamma = \gamma_f$ to flare completion when $\gamma_c \approx 0$, sec
t_{Fl}	Float time, time from the completion of flare ($\gamma_c \approx 0$) to touchdown, sec
$t_{\eta\beta}$	Time for the Dutch roll component of the sideslip response to reach the n th local maximum for a right step or pulse aileron-control command, or the n th local minimum for a left command. In the event a step control input cannot be accomplished, the control shall be moved as abruptly as practical and, for purposes of this definition, time shall be measured from the instant the cockpit control deflection passes through half the amplitude of the commanded value. For pulse inputs, time shall be measured from a point halfway through the duration of the pulse.
T_2	Time to double amplitude, $T_2 = \frac{-0.693}{\zeta\omega_n}$ for an oscillation, $T_2 = -0.693\tau$ for a first-order divergence, sec
$\frac{1}{T_{1/2}}$	Reciprocal of time to damp to half amplitude, $1/T_{1/2} = \zeta\omega_n/0.693$ for an oscillation, $1/T_{1/2} = 0.693\tau$ for a first-order convergence, sec ⁻¹
$\frac{1}{T_{es}}$	Inverse time constant of first-order representation of elevator-servo dynamics, sec ⁻¹
$\frac{1}{T_{h_1}}$	Lowest-frequency zero of the altitude-elevator transfer function
$\frac{1}{T_{\theta_1}}, \frac{1}{T_{\theta_2}}$	The first-order zeroes of the constant-speed attitude-elevator transfer function, sec ⁻¹
u	Incremental velocity along the x reference axis, ft/sec
u_g	Random gust velocity along the x body axis, ft/sec
v	Incremental velocity along the y reference axis, ft/sec
v_g	Random gust velocity along the y body axis, ft/sec
v'_m	Generalized discrete gust velocity, positive along the positive airplane body axes, $m=x, y, z$, ft/sec
V	Airspeed, ft/sec unless otherwise noted
$(V_{AV})_f$	Average speed during the flare, ft/sec unless otherwise noted

Symbols

V_{fc}	Speed at flare completion or speed at float initiation, ft/sec, unless otherwise noted
V_{fi}	Speed at flare initiation, ft/sec unless otherwise noted
V_{max}	Maximum service speed, ft/sec unless otherwise noted
V_{min}	Minimum service speed, ft/sec unless otherwise noted
$V_{R/c}$	Speed for maximum rate of climb, ft/sec unless otherwise noted
V_S	<p>Stall speed (equivalent airspeed), at 1 g normal to the flight path, defined as the highest of:</p> <ul style="list-style-type: none"> - speed for steady straight flight at $C_{L_{max}}$, the first local maximum of the curve of lift coefficient (L/qS) vs. angle of attack which occurs as C_L is increased from zero - speed at which abrupt controllable pitching, rolling or yawing occurs; i.e., loss of control about a single axis - speed at which intolerable buffet or structural vibration is encountered <p>(Note that 3.1.9.2.1 allows an alternative definition of V_S in some cases.)</p>
V_{TD}	Speed at touchdown, ft/sec unless otherwise noted
V_0	Initial flight path velocity, ft/sec
V_{0max}	Maximum operational speed, ft/sec unless otherwise noted
V_{0min}	Minimum operational speed, ft/sec unless otherwise noted
W	Weight of the airplane, lb
w	Incremental velocity along the z reference axis, ft/sec
w_g	Random gust velocity along the z body axis, ft/sec
x	Body-fixed axis of the airplane, along the projection of the undisturbed (trim or operating-point) velocity onto the plane of symmetry, with its origin at the c.g.
x	Horizontal distance over or along the ground, ft

Symbols

x_f	Horizontal distance traveled during flare, ft
x_{FL}	Horizontal distance traveled during float, ft
X	Force along the x axis, aerodynamic plus thrust, lb
X_i	$= \frac{1}{m} \frac{\partial X}{\partial i}$, where $i = \alpha, \dot{\alpha}, \delta_e, \theta, q, u$
y	Body-fixed axis of the airplane perpendicular to the plane of symmetry directed out the right wing, with its origin at the c.g.
Y	Side force along the y axis, aerodynamic plus thrust component, lb
Y_i	$= \frac{1}{mV} \frac{\partial Y}{\partial i}$, $i = \beta, \dot{\beta}, \delta_{AS}, \delta_{RP}, p, r$
z	Body-fixed axis of the airplane, directed downward perpendicular to the x and y axes, with its origin at the c.g.
Z	Force along z axis, lb
Z_i	$= \frac{1}{m} \frac{\partial Z}{\partial i}$, $i = \alpha, \dot{\alpha}, \delta_e, \theta, q, u$
α	Angle of attack, the angle in the plane of symmetry between the fuselage reference line and the tangent to the flight path at the airplane center of gravity, rad unless otherwise noted
α_0	Angle of attack for zero lift, rad unless otherwise noted
α_s	The stall angle of attack at constant speed for the configuration, weight, center-of-gravity position and external-store combination associated with a given Airplane Normal State; defined as the highest of the following: <ul style="list-style-type: none"> - Angle of attack for the highest steady load factor, normal to the flight path, that can be attained at a given speed or Mach number - Angle of attack, for a given speed or Mach number, at which abrupt uncontrollable pitching, rolling or yawing occurs, i.e., loss of control about a single axis - Angle of attack, for a given speed or Mach number, at which intolerable buffeting is encountered

Symbols

β	Sideslip angle at the center of gravity, angle between undisturbed flow and plane of symmetry. Positive, or right, sideslip corresponds to incident flow approaching from the right side of the plane of symmetry, rad unless otherwise noted
$\Delta\beta_{max}$	Maximum sideslip excursion at the c.g., occurring within two seconds or one half-period of the Dutch roll, whichever is greater, for a step aileron-control command, rad unless otherwise noted
$\bar{\rho}$	Atmospheric density decay parameter defined by $\bar{\rho} = -\frac{1}{\rho} \frac{d\rho}{dh}$
γ	Climb angle, $= \sin^{-1} \frac{\text{vertical speed}}{\text{true airspeed}}$, positive for climb, rad unless otherwise noted
$\gamma_{AV,FL}$	Average flight path angle in the float, rad unless otherwise noted
γ_{fc}	Flight path angle at flare completion, rad unless otherwise noted
γ_{fi}	Flight path angle at flare initiation or equilibrium glide angle at flare initiation, rad unless otherwise noted
γ_g	Flight path angle during equilibrium glide, rad unless otherwise noted
Δ	Used in combination with other parameters to denote a change from the initial value
δ_a	Aileron surface deflection, rad unless otherwise noted
δ_e	Elevator surface deflection, rad unless otherwise noted
δ_r	Rudder surface deflection, rad unless otherwise noted
δ_{RP}	Rudder pedal deflection, in.
ζ_{cs}	Damping ratio of the elevator feel system
ζ_d	Damping ratio of the Dutch roll oscillation
ζ_p	Damping ratio of the phugoid oscillation
ζ_{RS}	Damping ratio of the roll-spiral oscillation

Symbols

ζ_{SP}	Damping ratio of the longitudinal short-period oscillation
θ	Pitch angle, angle between the fuselage reference line and the horizontal, rad unless otherwise noted
ρ	Air density, slug/ft ³
σ	Real part of a complex dynamic root, sec ⁻¹
σ	Root-mean-square gust intensity, where $\sigma^2 = \int_0^\infty \Phi(\Omega) d\Omega = \int_0^\infty \phi(\omega) d\omega$
σ_{0EFF}	Effective PIO parameter
$\sigma_u, \sigma_v, \sigma_w$	Root-mean-square intensities of u_g, v_g, w_g respectively
τ_R	First-order roll mode time constant, positive for a stable mode, sec
τ_s	First-order spiral mode time constant, positive for a stable mode, sec
$1/\tau_u$	First-order zero of velocity-elevator transfer function, sec ⁻¹
$1/\tau_\eta$	First-order zero of flight path-elevator transfer function, sec ⁻¹
ϕ	Bank angle measured in the y - z plane, between the y axis and the horizontal, rad unless otherwise noted
ϕ_i	Initial peak magnitude in bank angle, rad unless otherwise noted
ϕ_t	Bank angle change in time t , in response to control deflection of the form given in 3.3.4, deg
$\frac{\phi_{osc}}{\phi_{AV}}$	A measure of the ratio of the oscillatory component of bank angle to the average component of bank angle following a rudder-pedals-free impulse aileron control command

$$\zeta_d \leq 0.2 : \frac{\phi_{osc}}{\phi_{AV}} = \frac{\phi_1 + \phi_3 - 2\phi_2}{\phi_1 + \phi_3 + 2\phi_2}$$

$$\zeta_d > 0.2 : \frac{\phi_{osc}}{\phi_{AV}} = \frac{\phi_1 - \phi_2}{\phi_1 + \phi_2}$$

where ϕ_1, ϕ_2 and ϕ_3 are bank angles at the first, second and third peaks, respectively

Symbols

$\left| \frac{\phi}{\beta} \right|_d$ At any instant, the ratio of amplitudes of the bank-angle and sideslip-angle envelopes in the Dutch-roll mode

$\bar{\Phi}_{u_g}(\Omega)$ Spectrum for u_g , where $\bar{\Phi}_{u_g}(\Omega) = V\phi_{u_g}(\omega)$, (ft/sec)²/(rad/ft)

$\bar{\Phi}_{v_g}(\Omega)$ Spectrum for v_g , where $\bar{\Phi}_{v_g}(\Omega) = V\phi_{v_g}(\omega)$, (ft/sec)²/(rad/ft)

$\bar{\Phi}_{w_g}(\Omega)$ Spectrum for w_g , where $\bar{\Phi}_{w_g}(\Omega) = V\phi_{w_g}(\omega)$, (ft/sec)²/rad/ft)

ψ_β Phase angle in a cosine representation of the Dutch roll component of sideslip - negative for a lag

$$\psi_\beta = \frac{-360}{T_d} t_{n_\beta} + (n-1)360 \text{ (degrees)}$$

with n as in t_{n_β} above

ω Temporal frequency, rad/sec, where $\omega = \Omega V$

ω Imaginary part of a complex dynamic root, sec⁻¹

ω_{ncs} Undamped natural frequency of the elevator feel system, rad/sec

ω_{nd} Undamped natural frequency of the Dutch roll oscillation, rad/sec

ω_{np} Phugoid undamped natural frequency, rad/sec

ω_{nsp} Undamped natural frequency of the short-period oscillation, rad/sec

ω_{rs} Roll-spiral undamped natural frequency, rad/sec

Ω Longitudinal spatial reduced frequency

$$\Omega = \frac{2\pi}{\lambda} \cdot \frac{\omega}{V}, \text{ rad/ft}$$

Abbreviations

c.g. Center of gravity

CL Climb

exp () The Napierian logarithmic base ($e = 2.718\dots$) raised to the power indicated

PA Power approach

Abbreviations

PIO Pilot-induced oscillation

PR Pilot rating

rms Root mean square

R/C Rate of climb

SAS Stability augmentation system

SSV Space shuttle vehicle

($\dot{}$) A dot above a symbol signifies the time derivative, e.g.,
 $\dot{\alpha} = \frac{d\alpha}{dt}$

()' A prime used in conjunction with ω_{nsp} , ζ_{sp} , ω_{ncs} , ζ_{cs} , $1/T_{cs}$ or $1/i_{cs}$ denotes stick-free values of the parameters when the stick-free and stick-fixed values are not the same (e.g., ω'_{nsp} or ζ'_{sp}). In particular, this notation is used when bobweights or $H_{\alpha e}$ caused the airplane response to feed back to the stick, unprimed parameters denoting values with the stick-fixed or the bobweight feedback loop open, and primed parameters denoting stick-free values with the feedback loop closed.

Section I INTRODUCTION

Presented here are the handling qualities requirements for lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds. These preliminary requirements are intended to apply to both large and small vehicles and vehicles from low to high cross-range based on hypersonic L/D and normal load factors. They do not apply to essentially ballistic re-entry vehicles with some limited cross-range capability. Since one of the purposes of many present and future experimental lifting re-entry vehicles is to investigate the performance, stability and control, and handling qualities in the lower atmosphere, the requirements presented here are subject to verification, revision, and extension based on additional flight test results. Handling qualities data will also be obtained from research programs in variable geometry aircraft, and in-flight and ground-based simulators.

At this point in the development of lifting re-entry vehicles, operational vehicles have not been designed, and total operational missions, flight phases, and the piloting tasks required to perform these missions have not as yet been adequately defined. An appropriate definition of flight phases and piloting tasks is dependent on a number of things such as mission, guidance and navigation systems, cockpit displays, and an adequate description of vehicle and control system dynamics. An operational lifting re-entry vehicle will be subjected to large variations in velocity, Mach number, and dynamic pressure. These large changes in the environmental conditions and vehicle dynamics must be considered in handling qualities requirements. Some of the problems associated with defining requirements throughout the flight envelope of lifting re-entry vehicles are discussed in Reference 1.

If the specification of handling qualities requirements is restricted to the lower speeds and terminal flight conditions of lifting re-entry, the operational mission requirements become reasonably clear. The pilot must be capable of successfully flying the vehicle to a predetermined landing site under what are considered operational flight conditions. The approach, flare, and landing may have to be performed under IFR as well as VFR conditions. Cruise, "go-around", or both will be valid parts of the mission when an adequate onboard propulsion system is provided.

When referring to "operational" lifting re-entry vehicles the word "operational" is used in the usual sense, i.e., a large number of military aircraft designed for a particular mission which will be flown by the usual population of military pilots trained to fly such aircraft. The lifting re-entry vehicles that have been built to date have usually been "one-of-a-kind" experimental vehicles flown by a limited number of skilled and highly trained experimental test pilots. The flight envelopes of these experimental vehicles have been restricted, and the vehicles have been flown generally under what are considered ideal flight conditions, such as VFR flight, large

landing fields, and limited cross-winds and gusts. It is also generally true that "one-of-a-kind" experimental vehicles in the past have been limited budget vehicles in terms of cost. Since experimental lifting re-entry vehicles are likely to be the rule rather than the exception for some time to come, the requirements of experimental vehicles as well as those of operational vehicles have been addressed in the preliminary handling qualities specification presented here. In general, minimum acceptable handling qualities for an experimental vehicle performing an experimental mission will be inadequate and unacceptable for the same vehicle under operational conditions, although some specific requirements may be the same for both missions. In general, acceptable handling qualities for the experimental mission will require improvement before the vehicle can be considered operational.

At the present time, serious consideration is also being given to very large specialized lifting re-entry vehicles such as the earth to orbit Space Shuttle Vehicle with Booster and Orbiter stages. These vehicles will not necessarily be "one-of-a-kind" vehicles, but they will be very sophisticated vehicles; they will fly the total boost to re-entry mission profile. Design requirements for optimizing payload will be very critical considerations. Reliability requirements for the vehicle and its subsystems will be high because of high program and vehicle costs, mission complexity, passenger safety, and vehicle and environmental unknowns. Some of the requirements in the handling qualities specification attempt to reflect these considerations, although it is realized that no actual experience exists for such vehicles upon which firm requirements can be based.

Handling qualities requirements for military aircraft are generally specified in terms of "open-loop" parameters of the vehicle that result in a certain level of handling qualities when the pilot performs certain closed-loop tasks. The same approach is used in the delineation of handling qualities requirements for lifting re-entry vehicles. In establishing requirements based on specific open-loop parameters similar to those in MIL-F-8785B(ASG), it is assumed that the vehicle is sustained in flight by primarily aerodynamic forces and controlled primarily by aerodynamic controls. This is a basic assumption made in specifying the handling qualities requirements of piloted airplanes (Reference 2). It is also assumed that the essential aspects of the vehicle dynamics, except for some very special exceptions, can be adequately defined by a set of linear differential equations with constant coefficients, and that the longitudinal and lateral-directional motions can be considered uncoupled, or only slightly coupled.

It is assumed in specifying particular modal parameters that these parameters adequately define the vehicle dynamics in response to atmospheric disturbances and to pilot command control inputs. Command control inputs and actual control surface motions are not the same for a vehicle whose dynamics are augmented by feedback loops to the control surface based on vehicle responses. The only basic premise made in assuming the same modal parameters for an augmented and unaugmented vehicle is that the vehicle response is essentially of the same order, at least from the point of view of handling qualities. This will be true if the transfer functions of the responses to

command control inputs have the same order characteristic equation and the same order numerators as is generally true of unaugmented vehicles whose dynamics can be defined adequately by constant coefficient equations of motion. For the augmented vehicle response to be essentially of the same order, any additional numerator or denominator terms introduced by the augmentation system must have sufficiently high break point frequencies, or be so arranged that they cancel one another such that small or negligible effects on the basic character of the vehicle responses, which occur at lower frequencies, are evident.

Primary and secondary flight control system requirements as they determine handling qualities are usually stated separately in terms of mechanical characteristics, control centering, breakout forces, phase lags, and other dynamic characteristics. This is the method used in MIL-F-8785B-(ASG) and is also followed here. Such a procedure assumes that the effect of control system dynamics on handling qualities can, in fact, be specified separately and can be related to the vehicle dynamics in the closed-loop situation in a simple way. It is recognized that this is not always possible and generalizations are not easy and must be approached with caution (see References 3, 4, and 5).

It has been proposed by some that a simpler way of specifying handling qualities requirements for a large variety of higher order vehicle responses that result from the use of various augmentation systems and feel systems, fly-by-wire or otherwise, is to specify acceptable time history response envelopes of the complete flight control system and vehicle combination. Such a form of specification may be possible in specific cases, but again such a generalized approach has yet to be devised as indicated by the results of Reference 4.

In view of what has been said above, and subject to the stated limitations as discussed above, the handling qualities requirements specified here apply to augmented as well as unaugmented vehicles. A few stability and control requirements in MIL-F-8785B(ASG) are specifically related to control surface motion rather than cockpit control motion. These requirements, when applied to airplanes, are requirements on the unaugmented airplane or the "bare airframe". These requirements have been modified in this lifting re-entry handling qualities specification so that they do not refer to control surface motions for the reasons stated in Section III when these particular requirements are discussed.

A vehicle sustained in flight primarily by aerodynamic forces implies a lower limit on the operational dynamic pressures. A lower limit on operational dynamic pressures ($\bar{q}_{o,min}$) for which the specified handling qualities are intended to apply can be determined from the following inequality (Reference 1).

$$(\bar{q}_o)_{min} \geq \frac{(\bar{K}_{g_o})_{min} W}{(C_{L_o})_{max} S} \quad (1)$$

$(\bar{K}_{g_o})_{min}$ = lower limit on the maximum attainable load factor in g's

$(C_{L_o})_{max}$ = maximum operational lift coefficient (not limited by control power)

W = vehicle weight in pounds

S = reference area of vehicle in square feet

For sustained level flight at minimum speed [maximum operational lift coefficient, $(C_{L_o})_{max}$], $\bar{K}_{g_o} = 1.0$. In equilibrium glide flight at minimum speed and constant glide angle (γ), $\bar{K}_{g_o} = \cos \gamma$. Under such conditions, assuming $L/D = 1.0$, the glide angle is 45 degrees and \bar{K}_{g_o} becomes 0.707. Although it is difficult to establish a definite lower limit on $(\bar{K}_{g_o})_{min}$, $(\bar{K}_{g_o})_{min} = 0.7$ appears reasonable and will be considered, in lieu of a better value, in determining the minimum value of dynamic pressure at which the handling qualities requirements presented are expected to apply. The value of $(C_{L_o})_{max}$ to be used in Equation (1) should be the maximum value attainable for the vehicle without limitations due to control power. Sustained operation of lifting re-entry vehicles at dynamic pressures lower than those specified by Equation (1) must be covered by special handling qualities requirements not considered in this specification.

If the operational flight conditions of the vehicle are such that the dynamic pressure variations with time are significant, handling qualities requirements for sustained flight under those dynamic conditions must be covered by special requirements not considered in this specification. Significant dynamic pressure variations with time can be established based on the following equation taken from Reference 1.

$$\frac{\Delta \bar{q}}{\bar{q}_o} = \left(-\bar{\beta} V_o \sin \gamma_o + \frac{2}{V_o} \frac{dV}{dt} \right) P \quad (2)$$

$$\bar{\beta} = .425 \times 10^{-4} \text{ ft}^{-1}$$

V_o = initial flight path velocity, ft/sec

γ_o = initial flight path angle, deg

dV/dt = acceleration along the flight path, ft/sec²

P = period of the dynamic motion, sec

The period (P), is the time of significance for the dynamics under consideration. In the case of short period motions, P may be the period of the longitudinal short period, the Dutch roll, or the roll mode time constant. In the case of longer period motions, P may be the phugoid period, or the spiral mode time constant. When P is large, the trajectory conditions V_0 , $\sin \alpha_0$, dV/dt need not differ greatly from the values in straight and level unaccelerated flight before the dynamic pressure changes become significant during the period of the motion.

How large the dynamic pressure changes must be before they significantly affect the dynamic motions has been investigated in a preliminary way in References 6 and 7. It is apparent from these preliminary results that both the character of the vehicle responses and the degree of damping that exists in the various vehicle response variables is affected. The effects appear to be largest for lightly damped responses. Thus, long period, lightly damped motions appear to be most strongly affected by time dependent dynamics. How these effects influence handling qualities, if at all, and how they might be considered in a handling qualities specification, have not been established at this time.

Some simple nonlinearities, such as nonlinear control derivatives, are treated by special requirements in the specification where appropriate. Significant nonlinearities in the nondimensional stability derivatives within the angle of attack and sideslip angles that will occur during dynamic oscillations of the vehicle must also be covered by special handling qualities requirements not considered in this specification.

Axis systems are important in establishing whether or not a particular vehicle meets particular handling qualities requirements. This is especially true of lateral-directional requirements and lifting re-entry vehicles which may be required to fly at rather large angles of attack during particular flight phases.

The modal parameters of the vehicle required to satisfy handling qualities requirements are referred to stability axes. This is an axis system fixed in the vehicle with its origin at the c.g. The x axis is in the plane of symmetry of the vehicle and is considered positive when pointing in the initial direction of the vehicle velocity vector with zero sideslip before the vehicle is disturbed. The z axis is perpendicular to the plane of symmetry and positive to the right when looking in the direction of flight. The y axis is in the plane of symmetry of the vehicle, perpendicular to the x axis, and positive when pointing down.

The validity of some of the lateral-directional requirements when they are applied to lifting re-entry vehicles flying at large angles of attack is open to some question since much of the handling qualities data upon which such requirements were based was obtained at more moderate angles of attack. The piloting tasks and pilot cues may be significantly different at large angles of attack.

None of the requirements is expected to apply to two or more stage lifting re-entry vehicles while the stages are attached or during separation. A few handling qualities requirements are stated for experimental lifting re-entry vehicles just after launch in level flight from another aircraft at altitude.

It should be stated that handling qualities requirements in general do not necessarily specify augmented vehicle requirements for an automatically controlled and stabilized vehicle. They are requirements for the vehicle when the pilot is in the control loop and he is required to perform particular tasks. In some cases augmented or unaugmented vehicle instability is allowed if the vehicle can be stabilized by the pilot. Good handling qualities for the pilot in performing particular tasks also do not in general assure a vehicle with good riding qualities or passenger comfort. Riding qualities may, however, be an important consideration in some lifting re-entry vehicle designs.

The specification presented is intended as a general handling qualities specification for lifting re-entry vehicles. It is expected that from this generalized specification a procurement specification for a specific vehicle will be written. The procuring activity will specify which requirement is to apply when alternate requirements are allowed. The procuring activity will also decide what is approved and what is not approved when approval of the procuring activity is required. At the discretion of the procuring activity, the procurement specification may delete requirements or have additional, or altered, specification requirements from those appearing in the general specification.

In establishing general flying qualities requirements for lifting re-entry vehicles, the format used is identical to that for piloted airplanes (Reference 2). This method appears to be most suitable at the present time during terminal flight in the lower atmosphere at low supersonic, transonic, and subsonic speeds. The paragraph numbering system in Section II is therefore identical to that used in MIL-F-8785B(ASG). This will facilitate reference to the revised piloted airplane flying qualities specification. Many of the requirements are taken directly from the piloted airplane specification with proper consideration of the differences between piloted airplanes and lifting re-entry vehicles. Some of the airplane specifications are not applicable to a lifting re-entry vehicle and they have been deleted. Other requirements applicable only to lifting re-entry vehicles have been added.

Some of the requirements for re-entry vehicles, as is the case for piloted airplanes, are related to equilibrium flight at constant altitude and changes from one equilibrium flight velocity to another at constant altitude. Such requirements assume that the airplane or vehicle is powered. A re-entry vehicle may fly much or all of the terminal glide and landing phases without power. Equilibrium flight at constant altitude is not possible for an unpowered vehicle. When such requirements are believed to be applicable to an unpowered re-entry vehicle, they are applied to equilibrium glide flight

at constant indicated airspeed in lieu of constant speed at constant altitude. Requirements associated with changes from one speed to another at constant altitude shall also apply during glide and gliding turns when the glide speed is changed from one equilibrium indicated airspeed to another. Flight at constant indicated airspeed in gliding flight is of significance to the pilot, especially in the very terminal phase of flight, and it is essentially flight at constant dynamic pressure. For gliding and climbing flight at other than constant dynamic pressure, i.e., nonequilibrium flight when the dynamic pressure changes significantly with time, the handling qualities are subject to the limitations previously discussed as defined by Equation 2.

The revised flying qualities requirements of piloted airplanes (Reference 2) are discussed in some detail in a user's guide (Reference 8). The purpose of the user's guide "is to explain the concept and philosophy underlying MIL-F-8785B(ASG) and to present some of the data and arguments upon which the requirements are based". Since many of the requirements presented in Section II are the same or similar to those for piloted airplanes, much of the data and many of the arguments upon which piloted-airplane requirements are based apply equally well, when properly interpreted, to lifting re-entry vehicles. In fact, some of the data presented in Reference 8 were obtained from ground and in-flight handling qualities research programs for lifting re-entry vehicle configurations. A user's guide of the magnitude of Reference 8, but applicable to lifting re-entry vehicles, is far too ambitious an undertaking at the present time. Lifting re-entry knowledge and data in the area of handling qualities is very limited. Section III, a more modest undertaking, presents the rationale and available data used in arriving at the re-entry vehicle handling qualities requirements of Section II. In Section III, only brief comments are made when the rationale and data available for particular requirements are the same or very similar to those used in establishing the requirements for MIL-F-8785B(ASG). When the rationale is significantly different, and the requirements are new and based on data not appearing in Reference 8, then the requirements are discussed in detail and the data is presented. It is hoped that Section III will some day evolve into a user's guide for lifting re-entry vehicles similar to Reference 8 for piloted airplanes. The importance of Section III in understanding both the limitations and the basis for the requirements presented in Section II cannot be overemphasized. Section III is especially important in any rational application of the requirements to a specific vehicle.

Section II
PRELIMINARY SPECIFICATION FOR THE FLYING QUALITIES OF
PILOTED RE-ENTRY VEHICLES DURING TERMINAL FLIGHT

1. SCOPE AND CLASSIFICATIONS

1.1 Scope. This specification contains the requirements for the flying qualities of lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds in the lower atmosphere.

1.2 Application. The requirements of this specification shall be applied to assure that no limitations on flight safety or on the capability to perform intended missions will result from deficiencies in flying qualities. The flying qualities for all lifting re-entry vehicles shall be in accordance with the provisions of this specification unless specific deviations are authorized by the procuring activity. Additional or alternate special requirements may be specified by the procuring activity.

1.3 Classification of vehicles. For the purposes of this specification, lifting re-entry vehicles shall be placed in one of the following Classes:

Class III Medium-to-heavy weight, low-to-medium cross-range
based on hypersonic $(L/D)_{max}$ and normal load factor.

Class IV Light-to-medium weight, medium-to-high cross-range
based on hypersonic $(L/D)_{max}$ and normal load factor.

The procuring activity will assign a vehicle to one of these Classes, and the requirements for that Class shall apply. When no Class is specified in a requirement, the requirements shall apply to both Classes. When operational missions so dictate, a vehicle of one Class may be required by the procuring activity to meet selected requirements ordinarily specified for vehicles of the other Class.

1.3.1 Operational or experimental designation. The letter (O) following a Class designation identifies a vehicle as an operational vehicle suitable for operational use; an experimental vehicle is similarly identified by (E). When no such differentiation is made in a requirement, the requirement shall apply to both an operational and experimental vehicle.

1.4 Flight Phase Categories. The Flight Phases have been combined into three Categories which are referred to in the requirement statements. These Flight Phases include the Flight Phases of both an operational and experimental vehicle. These Flight Phases shall be considered in the context of the mission of either an operational or experimental vehicle so that there will be no gap between successive Phases of any flight and so that transition from one Phase

to the next will be smooth. When no Flight Phase or Category is stated in a requirement, that requirement shall apply to all three Categories. In certain cases, requirements are directed at specific Flight Phases identified in the requirements. Flight Phases descriptive of both operational and experimental missions of lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds in the lower atmosphere have been categorized as follows:

Nonterminal Flight Phases:

Category A - Those nonterminal Flight Phases that require precise but only moderate maneuvering. Accurate flight-path control and precise tracking may be required. Included in this Category are:

- a. Air launch
- b. Powered boost
- c. High altitude, high speed cruise
- d. Transition (high to low angles of attack)

Category B - Those nonterminal Flight Phases that are normally accomplished using gradual maneuvers without precision tracking or very accurate flight-path control. Included in this Category are:

- a. Powered climb (not boost)
- b. Coast (unpowered)
- c. Cruise (low speed)
- d. Terminal area descent

Terminal Flight Phases

Category C - Terminal Flight Phases that require precise flight-path control and may require rapid maneuvering. Included in this Category are:

- a. Takeoff
- b. Emergency abort
- c. Approach
- d. Go-around
- e. Landing flare, float, and touchdown

When necessary, recategorization or addition of Flight Phases or delineation of requirements for special situations will be accomplished by the procuring activity.

1.5 Levels of flying qualities. Where possible, the requirements of section 3 have been stated in terms of three values of the stability and control parameters being specified. Each value is a minimum condition to meet one of three Levels of acceptability related to the ability of the vehicle to complete the phases of its mission. The Level of flying qualities specified has meaning only in the context of the vehicle missions and classification, and whether the vehicle is to be considered operational or experimental.

The Levels are:

- | | |
|---------|--|
| Level 1 | Flying qualities clearly adequate for the mission Flight Phase |
| Level 2 | Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists. |
| Level 3 | Flying qualities such that the vehicle can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. All Flight Phases that can be terminated can be safely terminated. All Flight Phases that must be completed can be completed safely. |

At the discretion of the procuring activity, Level 3 flying qualities may not be allowed based on specific vehicle and mission considerations. This will be done only after consultation between the procuring activity and the contractor.

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issue in effect, form a part of this specification to the extent specified herein. Specific deviations from these documents, including any corrections, deletions, and additions, will be established by the procuring activity as required to make them applicable to an operational and experimental lifting re-entry vehicle.

SPECIFICATIONS

- | | |
|-------------|--|
| MIL-F-9490 | Flight Control Systems - Design, Installation and Test of, Piloted Aircraft, General Specification for |
| MIL-C-18244 | Control and Stabilization Systems, Automatic, Piloted Aircraft, General Specification for |
| MIL-F-18372 | Flight Control Systems, Design, Installation and Test of, Aircraft (General Specification for) |
| MIL-S-25015 | Spin Requirements for Airplanes |
| MIL-W-25140 | Weight and Balance Control Data (for Airplanes and Rotorcraft) |

STANDARDS

MIL-STD-756 Reliability Predictions

SPECIAL SPECIFICATIONS AND STANDARDS

The procuring activity may find it necessary to establish special specifications and standards for lifting re-entry vehicles. When such specifications and standards relate to flying qualities requirements they form a part of this specification as established by the procuring activity. The procuring activity shall inform the contractor of any such special specifications and standards on the date of invitation for bids or request for proposals.

(Copies of documents required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

3. REQUIREMENTS

3.1 General Requirements

3.1.1 Missions. The procuring activity will specify the missions to be considered by the contractor in designing the vehicle to meet the flying qualities requirements of this specification. For an operational vehicle these operational missions will include the entire spectrum of intended operational usage. For an experimental vehicle the missions will include the entire spectrum of intended experimental use of the vehicle.

3.1.2 Loadings. The contractor shall define the envelope of center of gravity and corresponding weights that will exist for each Flight Phase. These envelopes shall include the most forward and aft center-of-gravity positions as defined in MIL-W-25140 as amended by the procuring activity to make it applicable to lifting re-entry vehicles. In addition, the maximum center-of-gravity excursions attainable through failures in systems or components, such as fuel sequencing, etc., should be defined by the contractor for each Flight Phase to be considered in the Failure States of 3.1.6.2. Within these envelopes, plus a growth margin to be specified by the procuring activity, and for the excursions cited above, this specification shall apply.

3.1.3 Moments of inertia. The contractor shall define the moments of inertia associated with all loadings of 3.1.2. The requirements of this specification shall apply for all moments of inertia so defined.

3.1.4 External stores. The requirements of this specification shall apply for all combinations of external stores required by the operational or experimental missions. The effects of external stores on the weight, moments of inertia, center-of-gravity position, and aerodynamic characteristics of the vehicle shall be considered for each mission Flight Phase. When the stores contain expendable loads, the requirements of this specification apply throughout

the range of store loadings. The external stores and store combinations to be considered for flying qualities design will be specified by the procuring activity. In establishing external store combinations to be investigated, consideration shall be given to asymmetric as well as to symmetric combinations.

3.1.5 Configurations. The requirements of this specification shall apply for all configurations required or encountered in the applicable Flight Phases of 1.4. A (crew-) selected configuration is defined by the positions and adjustment of the various selectors and controls available to the crew such as SAS gains, longitudinal and lateral-directional bias of control surfaces, wing deployment, flap setting, spoiler or drag brake settings, fixed power settings or power off, and landing gear position. Control surface positions shall not include the positions of controls such as rudder, ailerons, and elevator from the bias position. Trim control, throttle control, and other selector positions which are normally varied continuously by the pilot in flying the vehicle are not considered in configuration definition. A configuration may include one or more SAS gains off. The selected configurations to be examined must be realistic and consistent with those required for performance and mission accomplishment and shall not be established arbitrarily to meet specific flying qualities requirements. Additional configurations to be investigated may be defined by the procuring activity.

3.1.6 State of the vehicle. The State of the vehicle is defined by the selected configuration together with the functional status of each of the vehicle components or systems, fixed power setting or power off, weight, moment of inertia, center-of-gravity position, and external store complement. The trim setting and the positions of the rudder, aileron, and elevator controls are not included in the definition of Vehicle State since they are often specified in the requirements.

3.1.6.1 Vehicle Normal States. The contractor shall define and tabulate all pertinent items to describe the Vehicle Normal (no component or system failure) State(s) associated with each of the applicable Flight Phases. These items shall include vehicle weight, moments of inertia, center-of-gravity position, power on or off, thrust setting, wing deployment position, landing gear position, control surface bias, SAS gain settings, and other factors specified by the procuring activity. These items may vary continuously over a range of values in a Flight Phase. This continuous variation shall be replaced by a limited number of values of the parameter in question which will be treated as specific States, and which include the most critical values and the extremes encountered during the Flight Phase in question.

3.1.6.2 Vehicle Failure States. The contractor shall define and tabulate all Vehicle Failure States which consist of Vehicle Normal States modified by one or more malfunctions in vehicle components or systems, for example, a discrepancy between a selected configuration and an actual configuration. Those malfunctions that result in center-of-gravity positions outside the center-of-gravity envelope defined in 3.1.2 shall be included. Also included are failures of one or more engines such as loss of normal thrust, failure of

an engine to start or stop when required during a particular Flight Phase. Failures occurring in any Flight Phase shall be considered in all subsequent Flight Phases.

For an experimental vehicle, the contractor may waive definition of all Vehicle Failure States. Only a selected number of important failures, such as a total SAS system failure may be defined or the contractor may define Vehicle Failure States in some alternate way. It must be demonstrated by the contractor to the satisfaction of the procuring activity that any alternate simplified procedure will include all the important Vehicle Failure States. Approval by the procuring activity is required before an alternate procedure of defining Vehicle Failure States will be allowed.

3.1.6.2.1 Vehicle Special Failure States. Certain components or combinations thereof, may have extremely remote probability of failure during a given flight. These failure probabilities may, in turn, be very difficult to predict with any degree of accuracy. Special Failure States of this type need not be considered in complying with the requirements of Section 3 if justification is submitted to and approved by the procuring activity.

3.1.7 Operational Flight Envelopes. The Operational Flight Envelopes define the boundaries in terms of certain combinations of speed, Mach number, altitude, dynamic pressure, load factor, and angle of attack at which the vehicle must be capable of operating in order to accomplish the missions of 3.1.1. Envelopes for each applicable Flight Phase shall be established with the guidance and approval of the procuring activity.

3.1.8 Service Flight Envelopes. For each Vehicle Normal State the contractor shall establish, subject to the approval of the procuring activity, Service Flight Envelopes, showing certain combinations of speed, Mach number, altitude, dynamic pressure, normal acceleration, and angle of attack derived from the vehicle limits as distinguished from mission requirements. For each applicable Flight Phase and Vehicle Normal State, the boundaries of the Service Flight Envelopes can be coincident with, or lie outside, the corresponding Operational Flight Envelopes, but in no case shall they fall inside these operational boundaries. In establishing Service Flight Envelopes for a powered vehicle, the thrust setting may vary from the Normal State thrust. The Service Flight Envelopes of an experimental vehicle may differ from those of an operational vehicle with the approval of the procuring activity. The boundaries of the Service Flight Envelopes shall be based on considerations discussed in 3.1.8.1, 3.1.8.2, 3.1.8.3, and 3.1.8.4.

3.1.8.1 Maximum service speed. The maximum service speed, V_{\max} or M_{\max} , for each altitude is the lowest of:

- a. The maximum permissible speed
- b. A speed which is a safe margin below the speed at which intolerable buffet, flutter, or structural vibration is encountered

- c. The maximum airspeed in a dive or steep glide from which recovery can be made at a safe altitude without penetrating a safe margin from loss of control, dangerous behavior, uncontrollable buffet, and without exceeding structural limits. For a powered vehicle the speed is that attained with maximum power. For an unpowered vehicle the recovery altitude is that from which a safe unpowered landing can be made. This speed is subject to the approval of the procuring activity.
- d. The maximum airspeed based on engine limitations.

With the approval of the procuring activity, maximum dynamic pressure as a function of altitude may be used in lieu of V_{max} or M_{max} to define maximum service speed at each altitude. It must be established to the satisfaction of the procuring activity that maximum dynamic pressure will be less than the maximum dynamic pressure determined from V_{max} or M_{max} as defined by a through d, or that maximum service speed or Mach number so defined is not applicable.

3.1.8.2 Minimum service speed. The minimum service speed, V_{min} or M_{min} , for each altitude is the highest of:

- a. $1.1V_S$
- b. $V_S + 10$ knots equivalent airspeed
- c. The speed below which full vehicle nose-up elevator control power and trim are insufficient to maintain straight, steady flight with power or glide flight without power, whichever is applicable
- d. The lowest speed at which level flight can be maintained with maximum power
- e. For an unpowered vehicle in a glide, the lowest speed from which recovery and a safe unpowered landing can be made that meets unpowered landing requirements. This speed is subject to the approval of the procuring activity.
- f. For an unpowered vehicle, the speed below which the equilibrium glide slope angle is excessive. This glide slope must be established with the approval of the procuring activity.
- g. For Category C Flight Phases: A speed limited by reduced forward field of view or extreme nose-up pitch attitude that would result in the tail or aft fuselage contacting the ground.
- h. At ground level, the lowest touchdown speed consistent with the application of maximum structural "slap down" loads on the nose gear.

With the approval of the procuring activity, minimum dynamic pressure as a function of altitude may be used in lieu of V_{\min} or M_{\min} to define minimum speed at each altitude. It must be established to the satisfaction of the procuring activity that the minimum dynamic pressure will be greater than the minimum dynamic pressure determined from V_{\min} or M_{\min} as defined by a through h, or that minimum service speed or Mach number so defined is not applicable.

3.1.8.3 Maximum service altitude. The maximum service altitude, h_{\max} , for a given speed is the lowest of:

- a. For a powered vehicle in cruise level flight, the altitude above which a rate of climb larger than 100 feet per minute cannot be maintained in unaccelerated flight with maximum power.
- b. For an unpowered vehicle, or a powered vehicle in unpowered flight, the altitude above which the dynamic pressure is less than 0.7 times the minimum service speed dynamic pressure when the minimum service speed at altitude is defined by 3.1.8.2.
- c. A maximum service altitude will be defined, based on vehicle trajectory conditions, below which the handling qualities requirements included in this specification are expected to apply. This altitude will be established through mutual agreement between the contractor and the procuring activity. This altitude will be used when the maximum service altitude is not adequately defined as indicated in a or b.

3.1.8.4 Service load factors. Maximum (minimum) service load factors, $n(+)$ [$n(-)$], shall be established as a function of speed or Mach number for several significant altitudes. The maximum (minimum) service load factor, when trimmed for $1 g \cos(\gamma)$ flight at a particular speed or Mach number shall be defined for a powered vehicle in level flight and an unpowered vehicle in equilibrium glide flight at constant indicated airspeed. The maximum (minimum) service load factor is the lowest (highest) algebraically of:

- a. The positive (negative) structural limit load factor
- b. The steady load factor corresponding to the minimum allowable stall warning angle of attack (3.4.2.2.2)
- c. The steady load factor at which the elevator control is in the full vehicle-nose-up (nose-down) position
- d. A safe margin below (above) the load factor at which intolerable buffet or structural vibration is encountered
- e. The steady load factor corresponding to the maximum (minimum) allowable angle of attack defined by other considerations (3.4.2.2). This maximum (minimum) angle of attack is subject to the approval of the procuring activity.

3.1.9 Permissible Flight Envelopes. The Permissible Flight Envelopes encompass all regions in which operation of the vehicle is both allowable and possible. These are the boundaries of flight conditions outside the Service Flight Envelope which the vehicle is capable of safely encountering. Stalls, high angle-of-attack flight, and moderate dives may be representative of permissible flight conditions of the vehicle. The Permissible Flight Envelopes define the boundaries of those areas in terms of speed, Mach number, altitude, dynamic pressure, normal acceleration, and angle of attack. Permissible flight conditions and maneuvers that define the Permissible Flight Envelopes must be established with the approval of the procuring activity.

3.1.9.1 Maximum permissible speed (minimum permissible angle of attack).

The maximum permissible speed or minimum permissible angle of attack for each altitude shall be the lowest of:

- a. Limit speed based on structural and heating considerations
- b. Limit speed based on engine considerations
- c. The speed at which intolerable buffet or structural vibration is encountered
- d. For a powered vehicle, the maximum airspeed at maximum power, in a glide or dive, from which recovery can be made safely without loss of control or other dangerous behavior, intolerable buffet or structural vibration, and without exceeding structural limits. This speed is subject to the approval of the procuring activity.
- e. For an unpowered vehicle, the maximum speed from which recovery and a safe unpowered landing can be made. This speed is subject to the approval of the procuring activity.
- f. Speed or angle of attack at which unsafe stability and control characteristics begin to develop.

3.1.9.2 Minimum permissible speed (maximum permissible angle of attack).

The minimum permissible speed or maximum angle of attack in 1 g equilibrium level flight or 1 g $\cos(\gamma)$ glide flight is V_S [stall speed (equivalent airspeed)] or α_{max} defined by the highest (when referring to speed) or lowest (when referring to angle of attack) of:

- a. Speed (angle of attack) for steady straight flight at C_{Lmax} , the first local maximum of the curve of lift coefficient vs angle of attack which occurs as C_L is increased from zero. The angle of attack established for gliding re-entry during particular Flight Phases will be used when larger than the angle of attack for C_{Lmax}
- b. Speed (angle of attack) at which abrupt uncontrollable pitching, rolling or yawing occurs, i.e., loss of control about any axis

- c. Speed (angle of attack) at which intolerable buffet or structural vibration is encountered.

The minimum permissible speed may also be defined by 3.1.9.2 1.

3.1.9.2.1 Minimum permissible speed (maximum permissible angle of attack) based on other considerations. For some lifting re-entry configurations, considerations other than maximum lift determine the minimum permissible speed or maximum angle of attack in 1 g level flight or $1 g \cos \gamma$ glide flight (e.g., ability to perform altitude corrections, excessive sink rate or steep glide angle, insufficient energy for a safe unpowered approach, ability to execute a go-around when powered, etc.). In such cases, an arbitrary angle of attack limit, or similar minimum speed and maximum load factor limits, shall be established for the Permissible Flight Envelope. Such limits are subject to the approval of the procuring activity. This defined minimum permissible speed or maximum angle of attack shall be used as V_S or α_{max} in all applicable requirements.

3.1.10 Application of Levels. Levels of flying qualities as indicated in 1.5 are employed in this specification in realization of the possibility that the vehicle may be required to operate under abnormal conditions. Such abnormalities that may occur as a result of either flight outside the Operational Flight Envelope, the failure of vehicle components, or both, are permitted to comply with a degraded Level of flying qualities as specified in 3.1.10.1 through 3.1.10.3.3.

3.1.10.1 Requirements for Vehicle Normal States. The minimum required flying qualities for Vehicle Normal States (3.1.6.1) for both an operational and an experimental vehicle are shown in table I.

TABLE I. Levels for Vehicle Normal States

Within the Operational Flight Envelopes	Within the Service Flight Envelopes
Level 1	Level 2

3.1.10.2 Requirements for Vehicle Failure States. When Vehicle Failure States exist (3.1.6.2), a degradation in the flying qualities is permitted only if the probability of encountering a lower Level than specified in 3.1.10.1 is sufficiently small. At intervals established by the procuring activity, the contractor shall determine, based on the most accurate available data, the probability of occurrence of each Vehicle Failure State per flight and the effect of that Failure State on the flying qualities within the Operational and Service Flight Envelopes. These determinations shall be based on MIL-STD-756 except that: (a) all vehicle components and systems are assumed to be operating for a period, per flight, equal to the largest operational mission time to be considered in designing the vehicle, and (b) each specific failure is assumed to be present at whichever point in the flight envelope being considered is most critical (in the flying qualities sense). From these Failure

State probabilities and effects, the contractor shall determine the overall probability, per flight, that one or more flying qualities are degraded to Level 2 because of one or more failures. The contractor shall also determine the probability that one or more flying qualities are degraded to Level 3. These probabilities shall be less than the values shown in table II except as noted below.

TABLE II. Levels for Vehicle Failure States

Probability of Encountering	Within Operational Flight Envelopes	Within Service Flight Envelopes
Level 2 after Failure	10^{-2} per flight	
Level 3 after Failure	10^{-4} per flight	10^{-2} per flight

In no case shall a Failure State (except an approved Special Failure State) degrade any flying qualities outside the Level 3 limit.

The probability of encountering Level 2 or Level 3 flying qualities as a result of failures shall be less than the numbers specified in table II with the following exceptions:

- a. For an experimental vehicle it may be impractical or impossible for the contractor to determine the probability of occurrence of each Vehicle Failure State. In lieu of such determination, the contractor must present justification to and obtain approval from the procuring activity for any alternate method of specifying the degradation in flying qualities to be permitted as a result of system failures. One alternate method might consider only a very limited number of critical failures and their effects on flying qualities and simultaneously reduce the probability of encountering degraded Levels due to those limited critical failures below the values in table II. Another alternate method is to associate degraded Levels with critical failures or total system failures, such as failure of the total SAS system.
- b. Based on important and imperative considerations for mission success and safety, the procuring activity may reduce the probability of encountering degraded flying qualities because of failures as shown in table II, even to the extent that degradation to Level 3 is so improbable that it is not allowed.

3.1.10.2.1 Requirements on the effects of specific failures. The requirements on the effects of specific types of failures, e.g., propulsion or flight control system, shall be met on the basis that the specific type of failure has occurred, regardless of its probability of occurrence.

3.1.10.3 Exceptions

3.1.10.3.1 Ground operation and Terminal Flight Phases. Some requirements pertaining to vehicle takeoff, landing, taxiing, or vehicle air launch involve operation outside the Operational, Service, and Permissible Flight Envelopes, as at V_S , operation on the ground, operation in the influence of an air launch vehicle flow field, etc. When requirements are stated at conditions such as these, the Levels shall be applied as if the conditions were in the Operational Flight Envelope.

3.1.10.3.2 When Levels are not specified. Within the Operational and Service Flight Envelopes, all requirements that are not identified with specific Levels shall be met under all conditions of component and system failure except approved Vehicle Special Failure States (3.1.6.2.1).

3.1.10.3.3 Flight outside the Service Flight Envelope. From all points in the Permissible Flight Envelope, it shall be possible to return the vehicle readily and safely to the Service Flight Envelope without exceptional pilot skill or technique, regardless of component or system failures. Stalls, rapid sink rate or steep glide angle, large angles of attack, and moderate dives are examples of Permissible Flight Envelope flight conditions from which recovery to the Service Flight Envelope will be required. The requirements on stall, dive characteristics, dive recovery devices, and approach to dangerous flight conditions shall also apply. Additional flight conditions in the Permissible Flight Envelope from which recovery to the Service Flight Envelope will be required may be established by the procuring activity.

3.2 Longitudinal flying qualities

3.2.1 Longitudinal stability with respect to speed.

3.2.1.1 Longitudinal trim stability. For Levels 1 and 2, there shall be no tendency for primary flight control variables (airspeed, dynamic pressure, or angle of attack) to diverge aperiodically when the vehicle is disturbed from trim with the cockpit controls fixed and with them free. In straight and level cruise flight equivalent airspeed, and in terminal gliding flight, indicated airspeed will be considered as primary flight variables. For those Flight Phases where the pilot is required to fly dynamic pressure or angle of attack in gliding flight, either of these may be used in lieu of airspeed as the primary flight variable. This requirement will be considered satisfied if the variation of elevator cockpit control force and elevator cockpit control position with the primary flight variable (airspeed, dynamic pressure, or angle of attack) are smooth and the local gradients stable with:

- a. Elevator, rudder, and aileron control surface bias fixed at the positions applicable for the particular Flight Phase.
- b. SAS gains applicable to the particular Flight Phase.

c. Trimmer and throttle controls not moved from trim settings.

d. $1/g \cos (\gamma)$ normal acceleration to the flight path.

The requirements shall cover a range about trim of ± 15 percent of the flight variable except where limited by the boundaries of the Service Flight Envelope. When airspeed is the flight variable, ± 50 knots in equivalent or indicated airspeed about trim, whichever is applicable, will be used in place of ± 15 percent of the flight variable. Stable gradients mean increasing pull forces and aft motions of the elevator control to maintain slower airspeeds, lower dynamic pressure, or larger angle of attack and the opposite to maintain faster airspeed, higher dynamic pressure, and smaller angles of attack. For Level 3, an aperiodic divergence of speed, dynamic pressure, or angle of attack from equilibrium trim is acceptable if the time to double amplitude is greater than 60 seconds. In all cases the term gradient does not include that portion of the control force or control position versus the primary flight variable within the preload breakout force or friction range and that portion of trim which is provided automatically and is not reflected in cockpit elevator control forces or motion.

3.2.1.1.1 Relaxation in transonic flight. The requirements of 3.2.1.1 may be relaxed in the transonic speed range provided any divergent vehicle motions or reversals in slope of elevator control force and elevator control position with speed, dynamic pressure, or angle of attack, whichever is applicable for the particular Flight Phase, is gradual and not objectionable to the pilot. In no case, however, shall the requirements of 3.2.1.1 be relaxed more than the following:

- a. Levels 1 and 2 - For center-stick controllers, no local force gradient shall be more unstable than 3 pounds per 0.01M nor shall the force change exceed 10 pounds in the unstable direction. The corresponding limits for wheel controllers are 5 pounds per 0.01M and 15 pounds, respectively.
- b. Level 3 - For center-stick controllers, no local force gradient shall be more unstable than 6 pounds per 0.01M nor shall the force ever exceed 20 pounds in the unstable direction. The corresponding limits for wheel controllers are 10 pounds per 0.01M and 30 pounds, respectively.

In applying these requirements to a vehicle flying in unpowered transonic glide flight, the vehicle shall be initially trimmed to glide at constant indicated airspeed, dynamic pressure, or angle of attack, whichever is applicable as the flight variable for a particular Flight Phase.

This relaxation does not apply to Level 1 requirements for any Flight Phases which require prolonged transonic operation, or when the transonic range covers a significant Mach number increment for Class III(O) and Class IV(O) vehicles. This relaxation may still apply to Level 1 for Class III(E) and Class IV (E) even though transonic operation is somewhat prolonged

if justification is provided to and approval is obtained from the procuring activity. In this case "prolonged transonic operation", and "significant Mach number increment" will be defined by the procuring activity.

3.2.1.1.2 Elevator control force variations during rapid speed or Mach number changes. When the vehicle is accelerated and decelerated rapidly through the operational speed, dynamic pressure, or angle of attack range and through the transonic speed or Mach number range by the most critical combination of changes in power, actuation of deceleration devices, during speed gliding and climbing turns, pullups, and landing flares, the magnitude and rate of the associated trim change shall not be so great as to cause difficulty in maintaining the desired load factor by normal piloting technique.

3.2.1.1.3 Elevator control force variations during angle of attack transitions. For those Flight Phases involving large angle of attack transitions over short periods of time, the requirements of 3.2.1.1 do not apply. During such transitions it is only required that the transition can be performed smoothly and the rate and magnitude of associated trim change shall not be so great as to cause difficulty in adequately controlling the angle of attack transition. Push forces of less than 50 pounds shall be required for a transition from zero stick force trim at high angles of attack to maintain trim at low angles of attack after transition. A pull force of less than 35 pounds shall be required for angle of attack transition from trim at low angle of attack to high angle of attack. These forces shall apply to both stick and wheel controllers.

3.2.1.2 Phugoid stability. The long-period airspeed oscillations which occur when the vehicle seeks a stabilized airspeed following a disturbance shall meet the requirements in table III. These requirements apply with the elevator control free and also with it fixed. They need not be met transonically in cases where 3.2.1.1.1 permits relaxation of the longitudinal trim requirements with airspeed.

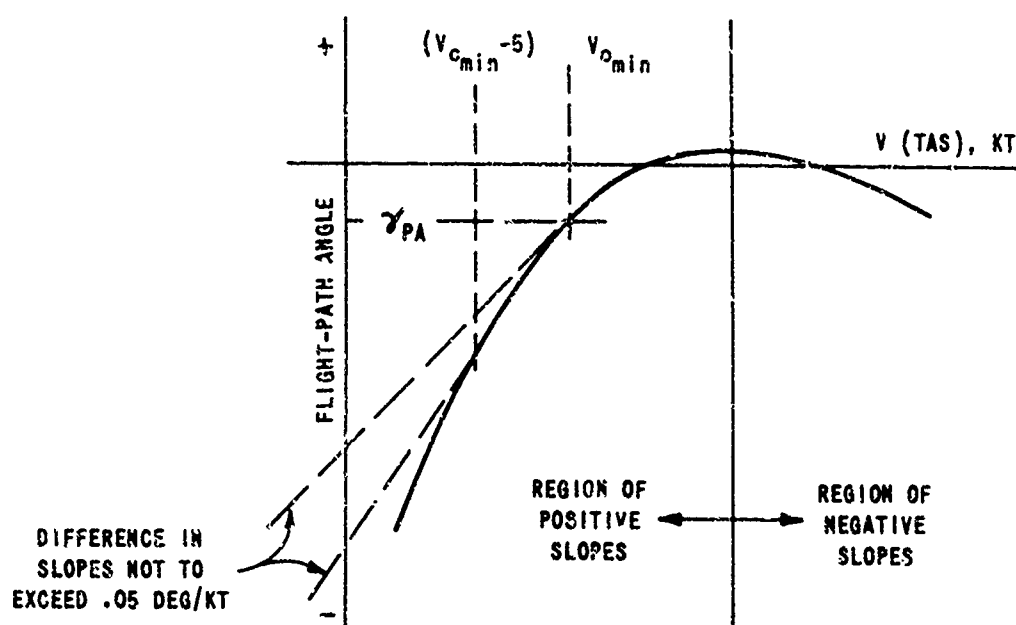
TABLE III. Phugoid Stability

	Class III and Class IV
Level 1	$\zeta_p = .04$
Level 2	$\zeta_p = 0$
Level 3	$T_2 \geq 55 \text{ sec}$

3.2.1.3 Flight-path stability. Flight-path stability is defined in terms of flight-path angle change where the airspeed is changed by the use of the elevator control only (throttle setting not changed by the crew). For the landing approach Flight Phase of the vehicle with power, the flight path angle versus true airspeed shall have a local slope at $V_{0 \min}$ which is negative or less positive than:

- a. Level 1 - 0.06 degrees/knot
- b. Level 2 - 0.15 degrees/knot
- c. Level 3 - 0.24 degrees/knot

The thrust setting shall be that required for normal approach glide at V_{0min} . The slope of the flight-path angle versus airspeed curve at 5 knots slower than V_{0min} shall not be more than 0.05 degrees per knot more positive than the slope at V_{0min} , as illustrated by:



For the landing approach Flight Phase of an unpowered vehicle, the flight-path angle versus indicated airspeed shall have a negative local slope at all speeds greater than the vehicle's operational touchdown speed (V_{0min}) minus 5 knots.

3.2.2 Longitudinal maneuvering characteristics.

3.2.2.1 Short-period response. The short-period response of angle of attack which occurs at approximately constant velocity, and which may be produced by abrupt control inputs, shall meet the requirements of 3.2.2.1.1 and 3.2.2.1.2. These requirements apply with the cockpit control free and with it fixed, for responses of any magnitude that might be experienced in service use. If oscillations are nonlinear with amplitude, the requirements shall apply to each cycle of the oscillation. In addition to meeting the numerical requirements of 3.2.2.1.1 and 3.2.2.1.2, the contractor shall show that Class III (0) and IV (0) have acceptable response characteristics in atmospheric disturbances.

Class III (E) and IV (E) vehicles can be designed for acceptable response characteristics with a lower rms level of atmospheric disturbances as suggested in section 3.7 with the approval of the procuring activity.

3.2.2.1.1 Short-period frequency and acceleration sensitivity. The short-period undamped natural frequency, $\omega_{n_{sp}}$, shall be within the limits shown in figures 1 and 2. Lower limits on (n/α) may be relaxed for Category C Flight Phases if adequate justification can be presented to, and approval is obtained from, the procuring activity. If suitable means of directly controlling normal force are provided, the lower bounds on both $\omega_{n_{sp}}$ and n/α during Category C Flight Phases may be relaxed.

For unpowered landings of Class III vehicles, it must be established by the contractor, to the satisfaction of the procuring activity, that the minimum short-period undamped frequencies allowed by figure 2 at low n/α 's are adequate for performing acceptable landing flares and floats to touchdown. When the frequencies are too low they must be raised to acceptable levels or other means of acceptable control must be provided and justified to the satisfaction of the procuring activity.

3.2.2.1.2 Short-period damping. The short-period damping ratio, ζ_{sp} , shall be within the limits of table IV.

TABLE IV. Short-Period Damping Ratio Limits

Class	Level	Category C		Categories A & B	
		min	max	min	max
III(O)	1	0.35	1.30	0.30	2.00
&	2	0.25	2.0	0.20	2.00
IV(O)	3	0.15*	--	0.15*	--
III(E)	1	0.35	1.30	0.18	2.00
&	2	0.20	2.0	0.07	2.00
IV(E)	3	0.05	--	0.03	--

*May be reduced at altitudes above 20,000 feet if approved by the procuring activity.

Maximum short-period damping for Category C Flight Phases may be relaxed if justification is presented to, and approval is obtained from, the procuring activity.

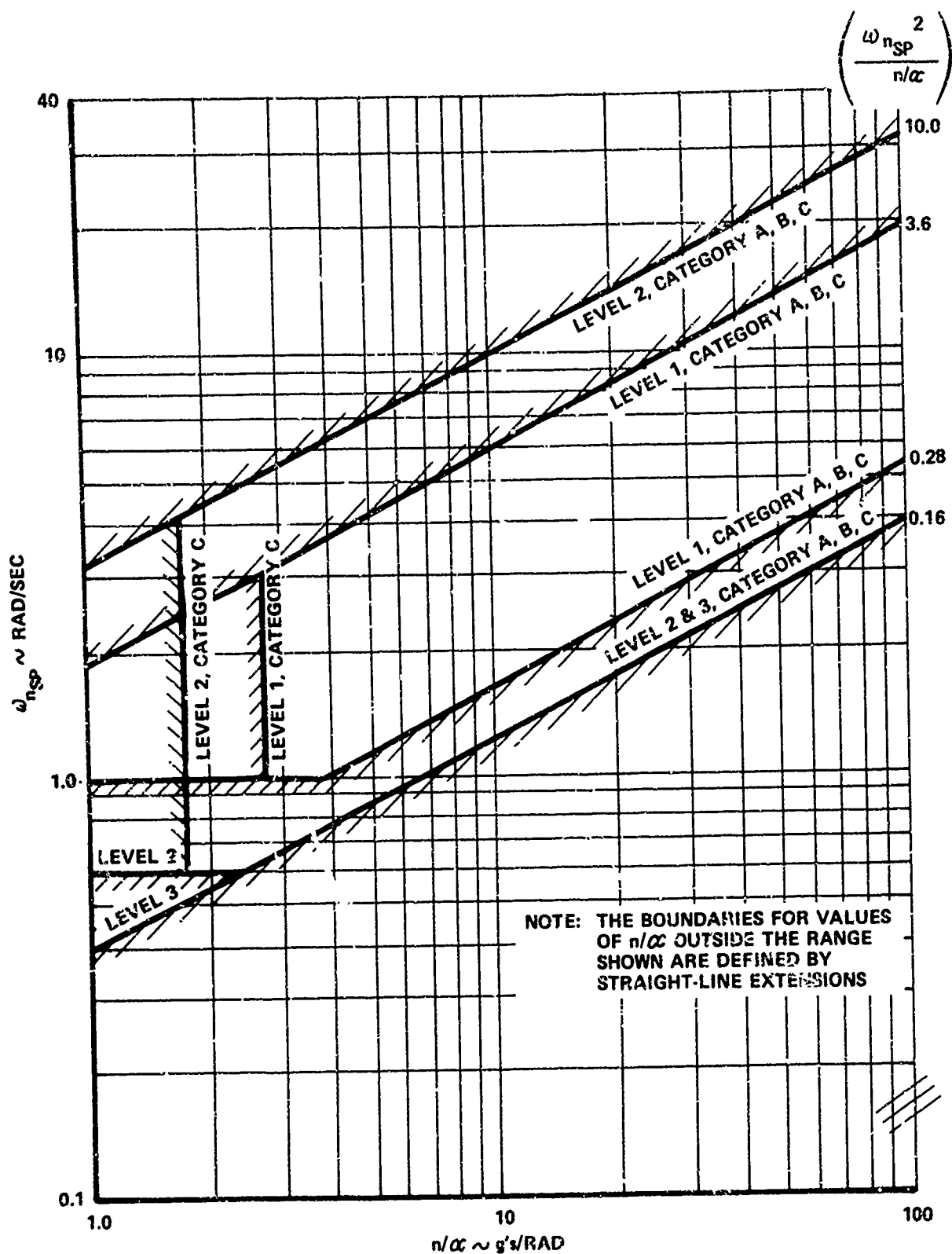


Figure 1 SHORT PERIOD FREQUENCY REQUIREMENTS -- CLASS IV

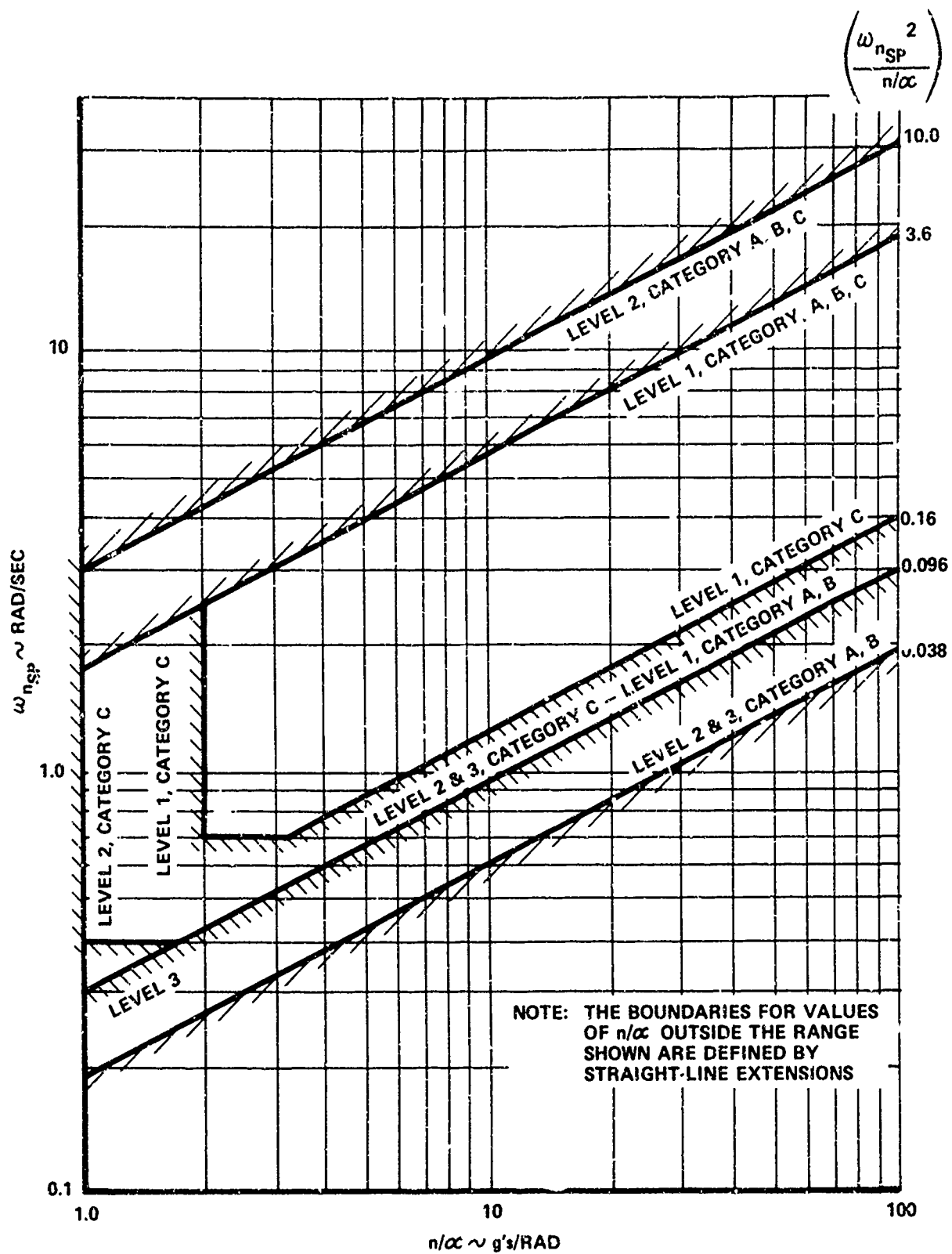


Figure 2 SHORT-PERIOD FREQUENCY REQUIREMENTS – CLASS III

3.2.2.1.3 Residual oscillations. With the flight control system gains required to meet the handling qualities requirements of this specification, any sustained residual oscillations due to limit cycle, structural resonance, etc., shall not interfere with the pilot's ability to perform the tasks required during the various Flight Phases of the vehicle. Oscillations in normal acceleration at the pilot's station greater than $\pm 0.05g$ will be considered excessive for any Flight Phase.

3.2.2.2 Control feel and control motion in maneuvering flight. In steady turning flight and in pullups at constant speed, increasing pull forces and aft motion of the elevator control are required to maintain increases in normal acceleration throughout the range of service load factors defined in 3.1.8.4. Increases in push force and forward cockpit control motion are required to maintain reductions for normal acceleration in pushovers.

3.2.2.2.1 Control forces in maneuvering flight. At constant speed in steady turning flight, pullups, pushovers, with power, and in steady gliding turns without power at constant indicated airspeed, the variations in elevator control force with steady-state normal acceleration shall be approximately linear. In general, a departure from linearity resulting in a local gradient which differs from the average gradient for the maneuver by more than 50 percent is considered excessive. All local force gradients shall be within the limits of table V. In addition, whenever the short-period frequency is near the upper boundary of frequency, F_s/n should be near the Level 1 upper boundaries of table V. This may be necessary to avoid abrupt response, sensitivity, or tendency toward pilot-induced oscillations. The term gradient does not include that portion of the force versus n curve within the preloaded breakout force or friction band.

3.2.2.2.2 Control motions in maneuvering flight. The elevator control motions in maneuvering flight shall not be so large or so small as to be objectionable. For Category C Flight Phases of unpowered vehicles, the average gradient of elevator control force per inch of elevator control deflection at constant speed shall not be less than 5 pounds per inch for Levels 1 and 2.

3.2.2.3 Longitudinal pilot-induced oscillations. There shall be no tendency for pilot-induced oscillations, that is, sustained or uncontrollable oscillations resulting from the effects of the pilot to control the vehicle. These requirements shall be met with the SAS gains that are necessary to meet the requirements of this specification. The requirements shall be met whether the oscillations are caused by short-period dynamics, feel-system dynamics, control-system dynamics, friction, freeplay, hysteresis, bobweights, aero-elastic coupling, or any other characteristics or combinations of these factors for the complete vehicle.

TABLE V. Elevator Maneuvering Force Gradient Limits

Level	<u>Center Stick Controllers</u>	
	Maximum Gradient $(F_s/n)_{\max}$, pounds/g	Minimum Gradient $(F_s/n)_{\min}$, pounds/g
1	$240/(n/\alpha)$ but not less than $\frac{56}{n_L - 1}^*$	The higher of $21/(n_L - 1)$ and 3.0
2	$360/(n/\alpha)$ not less than $85/(n_L - 1)^*$	The higher of $18/(n_L - 1)$ and 3.0
3	56.0 but not less than $360/(n/\alpha)$	3.0
* For $n_L < 3$, $(F_s/n)_{\max}$ is 28.0 for Level 1 and 42.5 for Level 2.		
Level	<u>Wheel Controllers</u>	
	Maximum Gradient $(F_s/n)_{\max}$, pounds/g	Minimum Gradient $(F_s/n)_{\min}$, pounds/g
1	$500/(n/\alpha)$ but not less than $120/(n_L - 1)$	The higher of $45/(n_L - 1)$ and 6.0
2	$775/(n/\alpha)$ but not less than $182/(n_L - 1)$	The higher of $38/(n_L - 1)$ and 6.0
3	240.0 but not less than $775/(n/\alpha)$	6.0

3.2.2.3.1 Transient control forces The peak elevator-control forces developed during abrupt maneuvers shall not be objectionably light, and the buildup of control force during the maneuver entry shall lead the buildup of normal acceleration. Specifically, the following requirement shall be met when the elevator control is pumped sinusoidally. For all input frequencies, the ratio of the peak force amplitude to the peak normal load factor amplitude at the c.g., measured from the steady oscillation, shall be greater than:

Center-Stick Controllers	3.0 pounds per g
Wheel Controllers	6.0 pounds per g

3.2.3 Longitudinal control.

3.2.3.1 Longitudinal control in unaccelerated flight. In all unaccelerated flight within the Service Flight Envelope, the attainment of all speeds shall not be limited by the effectiveness of the longitudinal control or controls.

3.2.3.2 Longitudinal control in maneuvering flight. Within the Operational Flight Envelope it shall be possible to develop, by use of elevator control alone, the maximum and minimum operational load factors. These requirements shall apply for Level 1 and Level 2. For Level 3 some relaxation will be allowed. Requirements for Level 3 will be established by mutual agreement between the contractor and procuring activity. This maneuvering capability is required at 1 g trim speed in level flight, with trim and throttle settings not changed by the crew, over a range about trim speed of ± 15 percent or ± 50 knots equivalent airspeed (except where limited by the boundaries of the Operational Flight Envelope). For an uncovered vehicle, the maneuvering capability is required in 1 g $\cos(\theta)$ glide flight.

3.2.3.3 Longitudinal control in takeoff. The effectiveness of the elevator control shall not restrict the takeoff performance of the vehicle and shall be sufficient to prevent overrotation to undesirable attitudes during takeoff. Satisfactory takeoffs shall not be dependent upon use of the cockpit trimmer control during takeoff or on complicated control manipulation by the pilot. For nose wheel vehicles it shall be possible to obtain, at $0.9 V_{min}$, the pitch attitude which will result in takeoff at V_{min} . These requirements shall be met on hard surface runways.

3.2.3.3.1 Longitudinal control during air launch. The speed and altitude conditions for air launch shall be established by the contractor with the approval of the procuring activity. During air launch, while the vehicle is under the influence of the flow field of the carrier aircraft, the vehicle elevator control effectiveness shall not restrict the launch performance of the vehicle and shall be sufficient to prevent contact with the carrier aircraft by a safe margin. Elevator control shall be adequate to preclude severe and unacceptable dynamic oscillations or overrotation to extreme nose-up or nose-down attitudes. Subsequent to launch, with the vehicle trimmed for launch, longitudinal control shall be sufficient to obtain required normal accelerations for satisfactory separation and to limit launch transient normal accelerations to satisfactory levels.

3.2.3.3.2 Longitudinal control force and travel in takeoff and during air launch. With the trim setting optional but fixed, the elevator-control forces required during takeoffs and air launches for which the vehicle is designed, shall be within the following limits:

Class IV - 30 pounds pull to 10 pounds push

Class III - 50 pounds pull to 20 pounds push

The elevator-control travel during takeoffs or air launches shall not exceed 75 percent of the total travel, stop to stop. The term takeoff includes the ground run, rotation and lift-off, the ensuing acceleration to V_{\max} (TO), and transient caused by assist cessation. Takeoff power shall be maintained until V_{\max} (TO) is reached, with the landing gear and high-lift devices retracted in the normal manner at speeds from V_{\min} (TO) to V_{\max} (TO).

3.2.3.4 Longitudinal control in landing. For powered landings, the elevator control shall be sufficiently effective in the landing Flight Phase in close proximity to the ground that:

- a. The geometric limited touchdown attitude can be maintained in level flight, or
- b. the lower of $V_s(L)$ or the guaranteed landing speed can be obtained.

For unpowered landings, the vehicle speed and elevator control effectiveness shall be sufficient in the landing Flight Phase in close proximity to the ground such that a trim incremental load factor of at least 0.5 can be attained at all equilibrium glide speeds down to minimum touchdown speed as defined in 3.2.3.4.2 without exceeding stall or the geometry limited touchdown attitude.

These requirements shall be met with the vehicle trim, control surface bias, longitudinal force control devices, and SAS gains set for the approach Flight Phase, at the required approach speed for the landing Flight Phase, prior to flare initiation. The requirements of 3.2.3.4 and 3.2.3.4.1 define Levels 1 and 2. For Level 3, it shall be possible to execute safe approaches and landings in the presence of atmospheric disturbances and crosswinds that are applicable to the vehicle as defined in this specification or by the procuring activity.

3.2.3.4.1 Longitudinal control forces in landing. The elevator control forces required to meet the requirements of 3.2.3.4 and 3.2.3.4.2 shall be pull forces and shall not exceed the following limits when the vehicle is trimmed for glide at the preflare approach speed.

Class IV - 35 pounds

Class III - 50 pounds

When flaps, landing gear, spoilers, or other lift or drag modulating devices are deployed or changed during the flare and float of an unpowered landing, the trim force change due to deployment in any sequence, including simultaneous deployment of two or more devices, shall not exceed the following limits:

Class IV - 5 pounds push or pull

Class III - 10 pounds push or pull

3.2.3.4.2 Power-off and unpowered longitudinal control requirements in landing. For power-off landings, when such are required, and the landing of unpowered vehicles, certain additional flare and float requirements shall be met. For purposes of this specification the flare will be initiated from equilibrium glide flight below an altitude of 2000 feet above ground level with an initial incremental load factor exceeding 0.1. The flare will be completed and the float initiated below 50 feet with a sink rate not exceeding 5 feet per second. The float will be considered completed as touchdown when any part of the landing gear contacts the surface. The flare altitude versus flare time shall be within the boundaries of figure 3. These requirements are for Class IV(E) and III(E) vehicles. For Class III(O) and IV(O) vehicles, the requirements will be established by the procuring activity after consultation with the contractor.

Minimum and maximum float time requirements are indicated in table VI and will apply to all Classes.

TABLE VI. Minimum and Maximum Float Time

	Minimum (seconds)	Maximum (seconds)
Level 1	15	30
Level 2	10	30
Level 3	5	30

These flare and float requirements for unpowered landings must be met with the flight-path stability requirements of 3.2.1.3 and the longitudinal control requirements of 3.2.3.4 for unpowered landings.

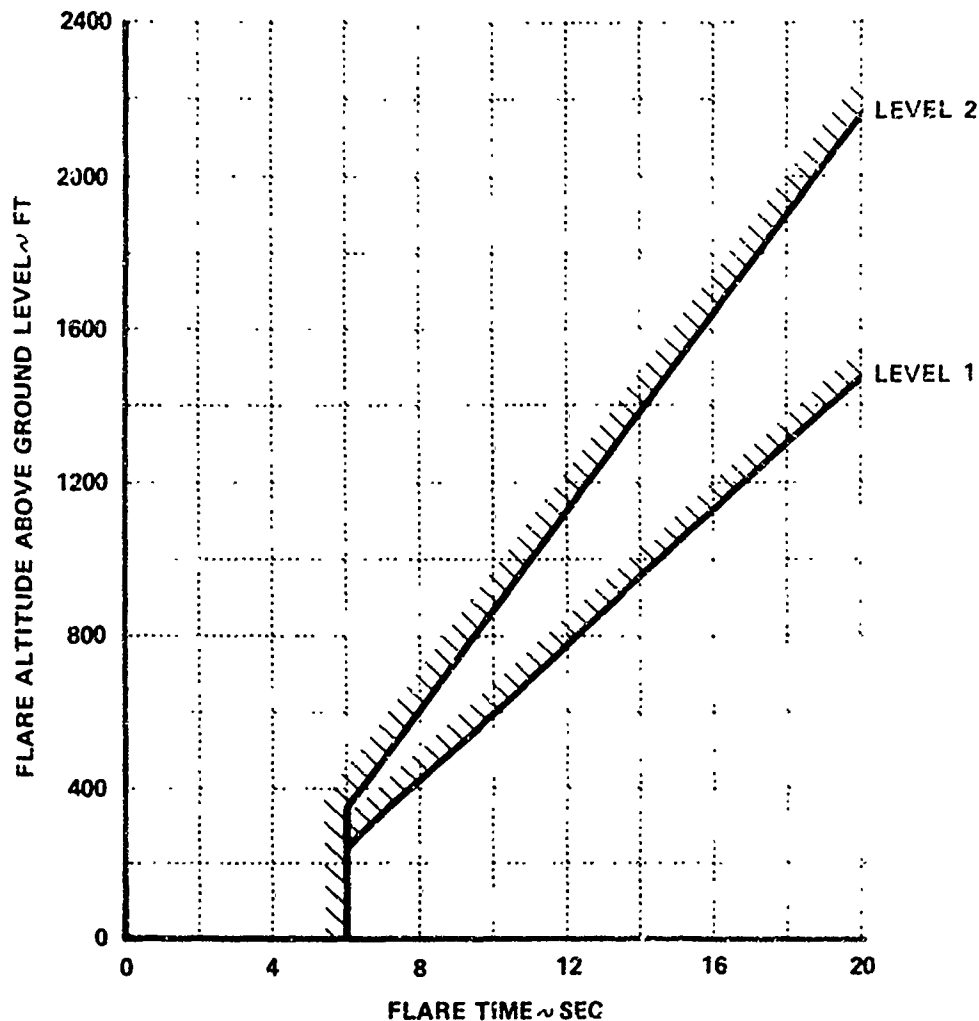


Figure 3 FLARE ALTITUDE AND FLARE TIME FOR UNPOWERED LANDINGS (CLASSES III (E) AND IV (E))

3.2.3.4.3 Elevator lift and longitudinal control in landing. Any adverse effects of elevator lift with pitch attitude changes must be sufficiently small so that they do not interfere significantly with the pilot's ability to make altitude and flight-path corrections during the approach, flare, and landing of powered and unpowered lifting re-entry vehicles.

3.2.3.5 Longitudinal control forces in dives - Service Flight Envelope. With a powered vehicle trimmed for level flight, and an unpowered vehicle trimmed for glide flight within the Service Flight Envelope, the elevator control forces in dives to all attainable speeds within the Service Flight Envelope shall not exceed 50 pounds push or 10 pounds pull for vehicles with

center-stick controllers, nor 75 pounds push or 15 pounds pull for vehicles with wheel controllers. In similar dives, but with trim optional following the dive entry, it shall be possible with normal piloting techniques to maintain the forces within the limits of 10 pounds push or pull for vehicles with center-stick controllers, and 20 pounds push or pull for vehicles with wheel controllers. The forces required for recovery from these dives shall be in accordance with the gradients specified in 3.2.2.2.1, although speed may vary during the pullout.

3.2.3.6 Longitudinal control forces in dives - Permissible Flight Envelope. With a powered vehicle trimmed for level flight and an unpowered vehicle trimmed for steady gliding flight, with trim optional in the dive, it shall be possible to maintain the elevator control force within the limits of 50 pounds push or 35 pounds pull in dives to all attainable speeds within the Permissible Flight Envelope. The force required for recovery from these dives shall not exceed 120 pounds. Trim and deceleration devices, etc., may be used to assist in recovery if no unusual pilot technique is required.

3.2.3.7 Longitudinal control in sideslips. With the vehicle trimmed with zero sideslip for straight and level powered flight or for unpowered equilibrium glide flight, the elevator-control force required to maintain constant indicated airspeed in steady sideslip, with up to 50 pounds of rudder pedal force in either direction, shall not exceed the elevator-control force that would result in a 1 g change in normal acceleration. In no case, however shall the elevator-control force exceed:

Center-stick controllers ----- 10 pounds pull to 3 pounds push

Wheel controllers ----- 15 pounds pull to 10 pounds push

If 50 pounds of pedal force result in a sideslip angle that exceeds lateral-directional sideslip requirements specified elsewhere, the same elevator-control forces shall apply at the maximum allowable sideslip angle. If a variation of elevator-control forces with sideslip does exist, it is preferred that increasing pull force accompany increasing sideslip, and that the magnitude and direction of the force change be similar for right and left sideslips. These requirements define Levels 1 and 2. For Level 3, there should be no uncontrollable pitching motions associated with the sideslips.

3.3 Lateral-directional flying qualities.

3.3.1 Lateral-directional mode characteristics.

3.3.1.1 Lateral-directional oscillations (Dutch roll). The frequency, ω_{nd} , and damping ratio, ζ_d , of the lateral-directional oscillations following a rudder disturbance input, shall exceed the minimum requirements in table VII. The requirements shall be met with cockpit controls fixed and with them free, in oscillations of any magnitude that might be experienced in operational use. If the oscillation is nonlinear with amplitude or time, the requirements shall

apply to each cycle of the oscillation. Residual oscillations may be tolerated only if the amplitude is sufficiently small that the motions are not objectionable and do not impair mission performance.

TABLE VII. Minimum Dutch Roll Frequency and Damping

Level	Flight Phase Category	Class	Min ζ_p^*	Min $\zeta_p \omega_{nd}$ rad/sec	Min ω_{nd} rad/sec
1	A & C	III	0.08	0.15	0.4**
	A & C	IV	0.08	0.15	1.0
	B	Both	0.08	0.15	0.4**
2	All	Both	0.02	0.05	0.4**
3	All	Both	0.02	--	0.4**

* The governing damping requirement is that yielding the larger value of ζ_p .

** Class III vehicles may be excepted from the minimum ω_{nd} requirements, subject to approval by the procuring activity, if the requirements of 3.3.2 through 3.3.2.4.1, 3.3.5 and 3.3.9.4 are met.

When $\omega_{nd}^2 |\phi/\beta|_d$ is greater than $20 (\text{rad/sec})^2$, the minimum $\zeta_p \omega_{nd}$ shall be increased above the $\zeta_p \omega_{nd}$ minimums listed above by:

$$\begin{aligned}
 \text{Level 1 - } \Delta \zeta_p \omega_{nd} &= .014 (\omega_{nd}^2 |\phi/\beta|_d - 20) \\
 \text{Level 2 - } \Delta \zeta_p \omega_{nd} &= .009 (\omega_{nd}^2 |\phi/\beta|_d - 20) \\
 \text{Level 3 - } \Delta \zeta_p \omega_{nd} &= .005 (\omega_{nd}^2 |\phi/\beta|_d - 20) \\
 &\text{with } \omega_{nd} \text{ in rad/sec.}
 \end{aligned}$$

3.3.1.1.1 Directional control margin. When automatic stabilization devices are used to overcome an aperiodic instability of the basic vehicle both the magnitude of the instability and the rudder control power shall be such that sufficient control moment can be commanded by the pilot in the critical direction through the use of the cockpit controls. Rudder control shall be sufficiently effective to balance the vehicle in yaw at all sideslip angles in the atmospheric disturbances of 3.7.3 and 3.7.4 for the operational vehicle and in a reduced level of atmospheric disturbances that will be specified by the procuring activity for the experimental vehicle.

3.3.1.1.2 Roll mode. The roll mode shall be stable and the time constant τ_R , shall be no greater than the appropriate values in table VIII.

TABLE VIII. Maximum Roll Mode Time Constant

Class	Flight Phase Category	Level 1	Level 2	Level 3
III-O	All	1.4 sec	3.0 sec	10 sec
IV-O	A & C	1.0 sec	1.4 sec	10 sec
	B	1.4 sec	3.0 sec	10 sec
III-E & IV-E	All	2.0 sec	5.0 sec	∞

3.3.1.3 Spiral stability. The combined effects of spiral stability, flight-control-system characteristics, and trim change with speed shall be such that following a disturbance in bank of up to 20 degrees, the time for the bank angle to double will be greater than the values in table IX. This requirement shall be met with the vehicle trimmed for wings-level, zero-yaw-rate flight with the cockpit controls free.

TABLE IX. Spiral Stability - Minimum Time to Double Amplitude

Class	Flight Phase Category	Level 1	Level 2	Level 3
III-O & IV-O	All	20 sec	12 sec	4 sec
III-E & IV-E	All	12 sec	8 sec	4 sec

3.3.1.4 Coupled roll-spiral oscillation. A coupled roll-spiral mode will not be permitted.

3.3.2 Lateral-directional dynamic response characteristics. Lateral-directional dynamic response characteristics are stated in terms of response to atmospheric disturbances and in terms of allowable roll rate and bank angle oscillations, sideslip excursions, aileron stick or wheel forces, and rudder pedal forces that occur during specified rolling and turning maneuvers. The requirements of 3.3.2.2, 3.3.2.3, and 3.3.2.4 apply for both right and left aileron commands of all magnitudes up to the magnitudes required to meet the roll performance requirements of 3.3.4 and 3.3.4.1.

3.3.2.1 Lateral-directional response to atmospheric disturbances.

Although no numerical requirements are specified, the combined effects of ω_{nd} , ξ_d , τ_k , $\chi(p/\beta)$, $|\phi/\beta|_d$, gust sensitivity, and flight-control-system nonlinearities shall be such that the vehicle will have acceptable response and controllability characteristics in atmospheric disturbances. In particular, the roll acceleration, rate and displacement responses to side gusts shall be investigated for the vehicle during glide, landing approach, flare and the float prior to touchdown at all angles of attack within the Operational and Service Flight Envelopes. The procuring activity shall specify the different types and magnitudes of atmospheric disturbances under which the operational and experimental vehicles shall have acceptable response and controllability characteristics.

3.3.2.2 Roll rate oscillations. Following a rudder-pedals-free step aileron control command, the roll rate at the first minimum following the first peak shall be of the same sign and not less than the following percentage of the roll rate at the first peak:

Level	Flight Phase	
	Category	Percent
1	A & C	60
	B	25
2	A & C	25
	B	0

For all levels, the change in bank angle shall always be in the direction of the aileron control command. The aileron command shall be held fixed until the bank angle has changed at least 90 degrees.

3.3.2.2.1 Additional roll rate requirements for small inputs. The value of the parameter ρ_{osc}/ρ_{AV} following a rudder-pedals-free step aileron control command, shall be within the limits shown in figure 4.

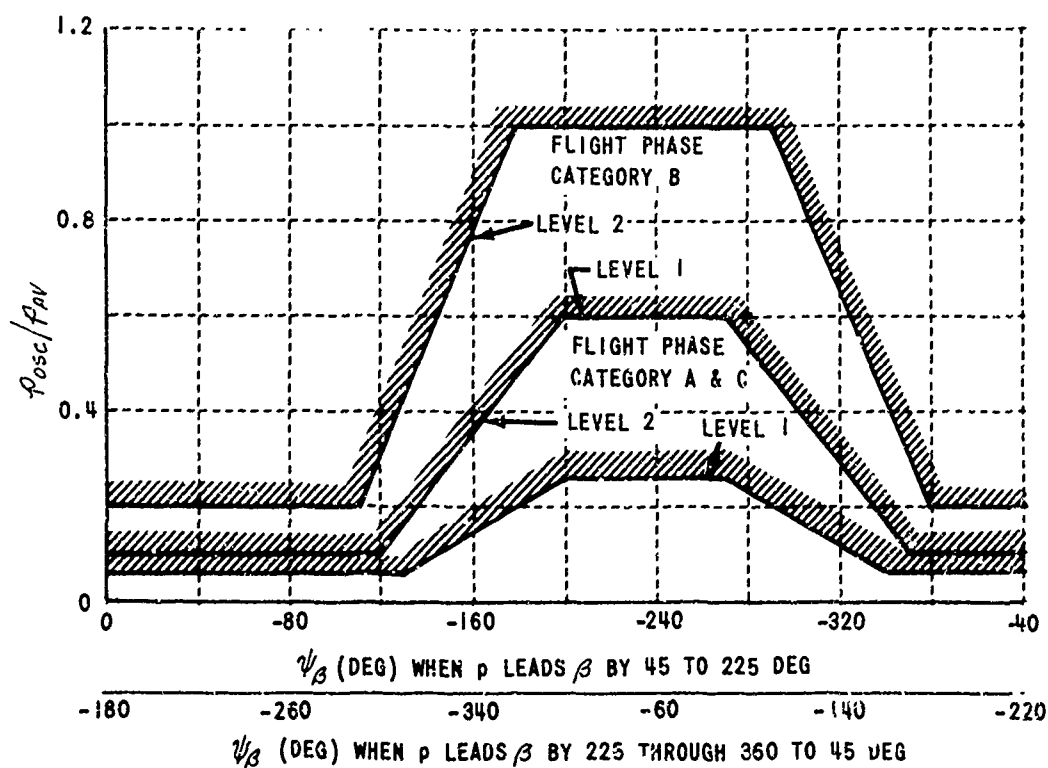


FIGURE 4 ROLL RATE OSCILLATION LIMITATIONS

3.3.2.3 Bank angle oscillations. The value of the parameter ϕ_{osc}/ϕ_{AV} following a rudder-pedals-free impulse aileron control command shall be within the limits in figure 5 for Levels 1 and 2. The impulse shall be as abrupt as practical within the strength limits of the pilot and the rate limits of the aileron control system.

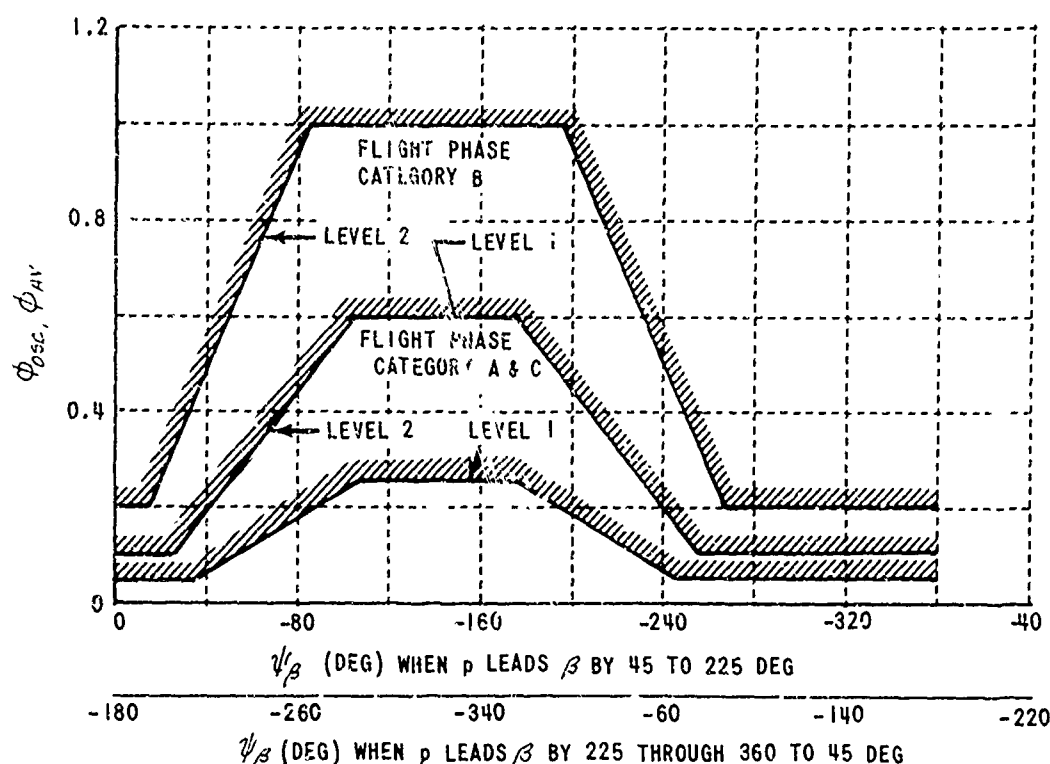


FIGURE 5 BANK ANGLE OSCILLATION LIMITATIONS

3.3.2.4 Sideslip excursions. The amount of sideslip following a rudder-pedals-free step aileron control command shall be less than the values specified herein. The aileron command shall be held fixed until the bank angle has changed at least 90 degrees.

Level	Flight Phase Category	Adverse Sideslip (Right roll command causes right sideslip)	Proverse Sideslip (Right roll command causes left sideslip)
1	C	6% degrees	2% degrees
	A & B	10% degrees	3% degrees
2	All	15% degrees	4% degrees

When the roll performance exceeds the requirements of 3.3.4 the maximum amount of sideslip allowed shall be determined assuming $\xi = 1.0$.

3.3.2.4.1 Additional sideslip requirements for small inputs. The amount of sideslip following a rudder-pedals-free step aileron control command shall be within the limits shown on figure 6 for Levels 1 and 2. This requirement shall apply for step aileron control commands up to the magnitude which causes a 60-degree bank angle change within one period of the Dutch roll oscillation or 2 seconds, whichever is longer.

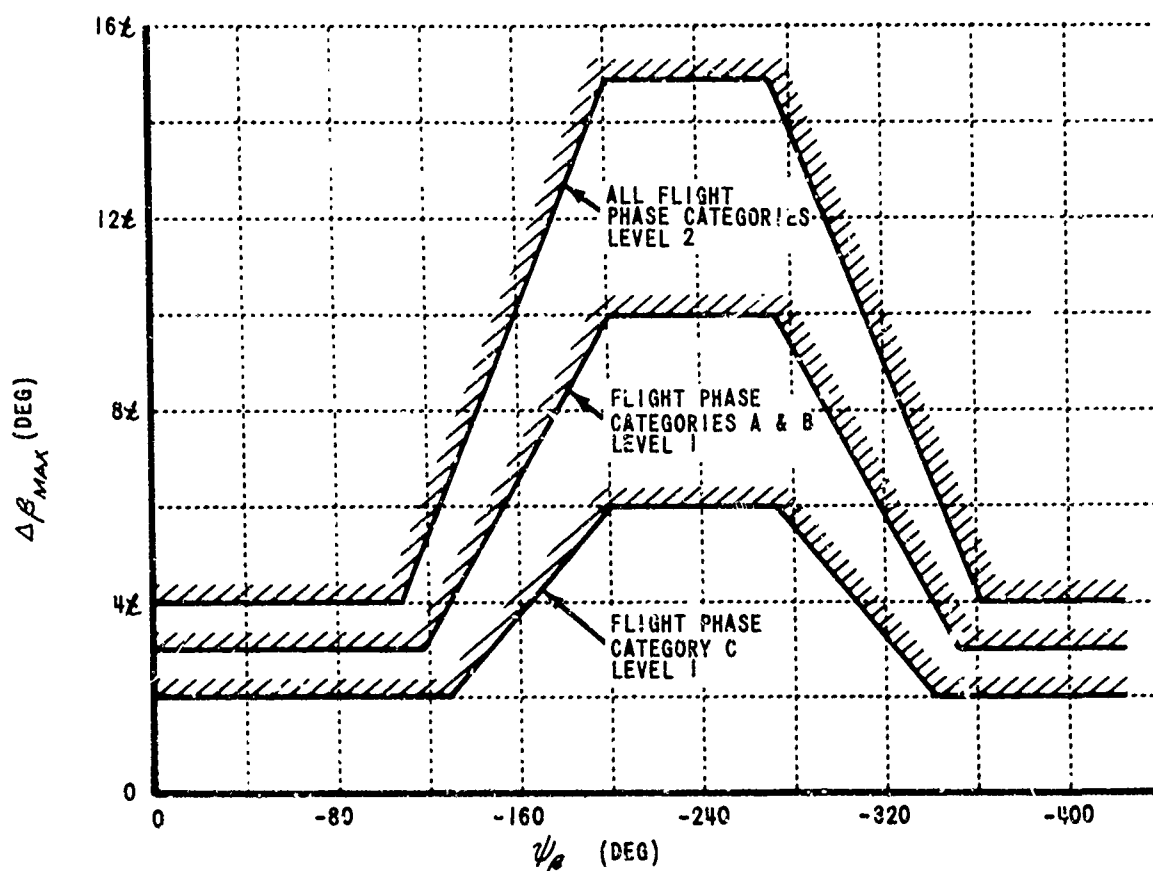


FIGURE 6 SIDESLIP EXCURSION LIMITATIONS

3.3.2.5 Control of sideslip in rolls. In the rolling maneuvers described in 3.3.4, but with the rudder pedals used for coordination for all Classes, directional-control effectiveness shall be adequate to maintain zero sideslip with a rudder pedal force not greater than 50 pounds for Class IV vehicles in Flight Phase Category C, Level 1 and 100 pounds for all other combinations of Class, Flight Phase Category, and Level.

3.3.2.6 Turn coordination. It shall be possible to maintain steady coordinated turns in either direction, using 60 degrees of bank for Class III vehicles, with a rudder pedal force not exceeding 40 pounds and aileron stick force not exceeding 5 pounds or an aileron wheel force not exceeding 10 pounds. These requirements constitute Levels 1 and 2 with the vehicle trimmed for wings-level straight flight.

3.3.3 Pilot-induced oscillations. There shall be no tendency for sustained or uncontrollable lateral-directional oscillations resulting from efforts of the pilot to control the vehicle.

3.3.4 Roll control effectiveness. Roll control effectiveness is specified in table X in terms of bank angle change in a given time, ϕ_t . Aileron control commands shall be initiated from zero roll rate in the form of abrupt inputs, with time measured from the initiation of control force application. Rudder pedals shall remain free for Class III-O and Class IV-O vehicles for Flight Phase Category C, Level 1. Otherwise, rudder pedals may be used to reduce sideslip that retards roll rate (not to produce sideslip that augments roll rate) if rudder pedal inputs are simple, easily coordinated with aileron-control inputs, and consistent with piloting techniques for the vehicle Class and mission. Roll control shall be sufficiently effective to balance the vehicle in roll throughout the Service Flight Envelope in the atmospheric disturbances of 3.7.3 and 3.7.4 for the operational vehicle and in a reduced level of atmospheric disturbances that will be specified by the procuring activity for the experimental vehicle.

TABLE X. Roll Control Effectiveness

Class	Flight Phase Category	Level 1	Level 2	Level 3
III-O and III-E	C	$\phi_t = 45^\circ$ in 3.2 sec	$\phi_t = 45^\circ$ in 4.1 sec	$\phi_t = 45^\circ$ in 5.4 sec
	A & B	$\phi_t = 30^\circ$ in 2.0 sec	$\phi_t = 30^\circ$ in 3.0 sec	$\phi_t = 30^\circ$ in 4.0 sec
IV-O and IV-E	C	$\phi_t = 45^\circ$ in 1.2 sec	$\phi_t = 45^\circ$ in 1.6 sec	$\phi_t = 45^\circ$ in 2.6 sec
	A & B	$\phi_t = 45^\circ$ in 1.2 sec	$\phi_t = 45^\circ$ in 1.6 sec	$\phi_t = 45^\circ$ in 2.1 sec

3.3.4.1 Roll response to aileron control force. Stick-controlled vehicles in Category C Flight Phases shall have a roll response to aileron force not greater than 7.5 degrees in 1 second per pound for Level 1, and not greater than 12.5 degrees in 1 second per pound for Level 2. For Category A Flight Phases, the stick roll sensitivity shall be not greater than 15 degrees in 1 second per pound for Level 1, and not greater than 25 degrees in 1 second per pound for Level 2. Stick-controlled vehicles in Category B Flight Phases shall have a roll response to aileron force not greater than 25 degrees in 1 second per pound for Level 1. In case of conflict between the requirements of 3.3.4.1 and 3.3.4.2, the requirements of 3.3.4.1 shall govern.

3.3.3 Pilot-induced oscillations. There shall be no tendency for sustained or uncontrollable lateral-directional oscillations resulting from efforts of the pilot to control the vehicle.

3.3.4 Roll control effectiveness. Roll control effectiveness is specified in table X in terms of bank angle change in a given time, ϕ_t . Aileron control commands shall be initiated from zero roll rate in the form of abrupt inputs, with time measured from the initiation of control force application. Rudder pedals shall remain free for Class III-O and Class IV-O vehicles for Flight Phase Category C, Level 1. Otherwise, rudder pedals may be used to reduce sideslip that retards roll rate (not to produce sideslip that augments roll rate) if rudder pedal inputs are simple, easily coordinated with aileron-control inputs, and consistent with piloting techniques for the vehicle Class and mission. Roll control shall be sufficiently effective to balance the vehicle in roll throughout the Service Flight Envelope in the atmospheric disturbances of 3.7.3 and 3.7.4 for the operational vehicle and in a reduced level of atmospheric disturbances that will be specified by the procuring activity for the experimental vehicle.

TABLE X. Roll Control Effectiveness

Class	Flight Phase Category	Level 1	Level 2	Level 3
III-O and III-E	C	$\phi_t = 45^\circ$ in 3.2 sec	$\phi_t = 45^\circ$ in 4.1 sec	$\phi_t = 45^\circ$ in 5.4 sec
	A & B	$\phi_t = 30^\circ$ in 2.0 sec	$\phi_t = 30^\circ$ in 3.0 sec	$\phi_t = 30^\circ$ in 4.0 sec
IV-O and IV-E	C	$\phi_t = 45^\circ$ in 1.2 sec	$\phi_t = 45^\circ$ in 1.6 sec	$\phi_t = 45^\circ$ in 2.6 sec
	A & B	$\phi_t = 45^\circ$ in 1.2 sec	$\phi_t = 45^\circ$ in 1.6 sec	$\phi_t = 45^\circ$ in 2.1 sec

3.3.4.1 Roll response to aileron control force. Stick-controlled vehicles in Category C Flight Phases shall have a roll response to aileron force not greater than 7.5 degrees in 1 second per pound for Level 1, and not greater than 12.5 degrees in 1 second per pound for Level 2. For Category A Flight Phases, the stick roll sensitivity shall be not greater than 15 degrees in 1 second per pound for Level 1, and not greater than 25 degrees in 1 second per pound for Level 2. Stick-controlled vehicles in Category B Flight Phases shall have a roll response to aileron force not greater than 25 degrees in 1 second per pound for Level 1. In case of conflict between the requirements of 3.3.4.1 and 3.3.4.2, the requirements of 3.3.4.1 shall govern.

3.3.4.2 Aileron control forces. The stick or wheel force required to achieve the roll control effectiveness in table X of 3.3.4 shall be less than the maximum in table XI. The minimum force shall be greater than the breakout force plus one-fourth and one-eighth the values in table XI for Levels 1 and 2, respectively. For Level 3, the minimum aileron control force shall be greater than the breakout force.

3.3.4.3 Linearity of roll response. There shall be no objectionable non-linearities in the variation of rolling response with aileron control deflection or force. Sensitivity or sluggishness in response to small aileron control deflections or forces shall be avoided.

TABLE XI. Maximum Aileron Control Force

Level	Class	Flight Phase Category	Maximum Stick Force (lb)	Maximum Wheel Force (lb)
1	III-O	A & B	25	50
		C	25	25
	IV-O	A & B	20	40
		C	20	20
2	III-O	A & B	30	60
		C	30	30
	IV-O	A & B	30	60
		C	20	20
3	III-O & IV-O	A11	35	70
A11	III-E & IV-E	A11	35	70

3.3.4.4 Wheel control throw. For vehicles with wheel controllers, the wheel throw necessary to meet the roll control effectiveness requirements specified in 3.3.4 shall not exceed 60 degrees in either direction. For completely mechanical systems, the requirement may be relaxed to 80 degrees.

3.3.4.5 Rudder-pedal-induced rolls. For Levels 1 and 2, it shall be possible to raise a wing by use of the rudder pedal alone, with right rudder pedal force required for right rolls and left rudder pedal force required for left rolls. For Level 1, with the aileron control free, it shall be possible to produce a roll rate of 3 degrees per second with an incremental rudder pedal force of 50 pounds or less. The specified roll rate shall be attainable from coordinated turns at up to ± 30 degrees bank angle with the vehicle trimmed for wings-level, zero-yaw-rate flight. For Levels 1 and 2, effective dihedral shall not be so great that use of rudder pedals adversely affects precision of bank angle control or causes excessively large roll rates.

3.3.5 Directional control characteristics. Directional stability and control characteristics shall enable the pilot to balance yawing moments and control yaw and sideslip. Sensitivity to rudder pedal forces shall be sufficiently high that directional control and force requirements can be met and satisfactory coordination can be achieved without unduly high rudder pedal forces, yet sufficiently low that occasional improperly coordinated control inputs will not seriously degrade the flying qualities.

3.3.5.1 Directional control with speed change. With the vehicle initially trimmed directionally with symmetric power, the trim change with speed shall be such that wings-level straight flight can be maintained over a speed range of ± 30 percent of the trim speed or ± 100 knots equivalent airspeed, whichever is less (except where limited by boundaries of the Service Flight Envelope). The rudder pedal forces shall not be greater than 40 pounds for Levels 1 and 2, and 180 pounds for Level 3, without retrimming.

3.3.5.1.1 Directional control with asymmetric loading. With the vehicle initially trimmed directionally in the asymmetric loading conditions specified in the contract at any speed in the Operational Flight Envelope, it shall be possible to maintain a wings-level straight flight path throughout the Operational Flight Envelope with rudder pedal forces not greater than 100 pounds for Levels 1 and 2 and not greater than 180 pounds for Level 3, without retrimming.

3.3.5.2 Directional control in go-around. For the vehicle with a landing engine, the response to thrust, configuration, and airspeed change during landing abort shall be such that the pilot can maintain straight flight during go-around initiated at speeds down to $V_S(PA)$. The rudder pedal forces shall not exceed 40 pounds for Levels 1 and 2 nor 180 pounds for Level 3.

3.3.6 Lateral-directional characteristics in steady sideslips. The requirements of 3.3.6.1 through 3.3.6.3.1 and 3.3.7.1 are expressed in terms of characteristics in rudder-pedal-induced steady, zero-yaw-rate sideslips with the vehicle trimmed for wings-level straight flight. For 3.3.6.1 through 3.3.6.3, sideslip angles shall be considered up to those produced or limited by:

- a. Full rudder pedal deflection, or
- b. 250 pounds of rudder pedal force, or

- c. maximum aileron control or surface deflection, or
- d. a maximum sideslip angle to be specified by the procuring activity for the operational and the experimental vehicles for the various Flight Phase Categories.

3.3.6.1 Yawing moments in steady sideslips. For the sideslips specified in 3.3.6, right rudder pedal deflection and force shall produce left sideslips, and left rudder pedal deflection and force shall produce right sideslips. The variation of sideslip angle with rudder pedal deflection and force shall be essentially linear for sideslip angles between + 5 degrees and -5 degrees for Levels 1 and 2, Flight Phase Categories A and B. For larger sideslip angles an increase in rudder pedal deflection shall always be required for an increase in sideslip. For Flight Phase Category C, linearity between rudder pedal deflection and sideslip and rudder pedal force and sideslip shall apply between + 10 degrees and -10 degrees for the operational vehicle and between + 5 degrees and -5 degrees for the experimental vehicle. Although the gradient of sideslip angle versus pedal deflection and sideslip angle versus rudder pedal force may be reduced outside the linear range specified, in no case shall this reduction be less than 50 percent of the linear gradient, except for Level 3, when the gradient must always be greater than zero. The term gradient does not include that portion of the rudder pedal force versus sideslip angle curve within the preloaded breakout force or friction band.

3.3.6.2. Side forces in steady sideslips. For the sideslips of 3.3.6, an increase in right bank angle shall accompany an increase in right sideslip, and an increase in left bank angle shall accompany an increase in left sideslip.

3.3.6.3 Rolling moments in steady sideslips. For the sideslips of 3.3.6, left aileron-control deflection and force shall accompany left sideslips, and right aileron-control deflection and force shall accompany right sideslips. For Levels 1 and 2, the variation of aileron-control deflection and force with sideslip angle shall be essentially linear.

3.3.6.3.1 Exception for go-around. The requirement of 3.3.6.3 may, if necessary, be waived for go-around if task performance is not impaired and no more than 50 percent of roll control power available to the pilot and no more than 10 pounds of aileron-control force, are required in a direction opposite to that specified in 3.3.6.3.

3.3.6.3.2 Positive effective dihedral limit. For Level 1, positive effective dihedral (right roll control for right sideslip and left roll control for left sideslip) shall never be so great that more than 50 percent of the roll control power available to the pilot and no more than 7.5 pounds of aileron-stick force or 15 pounds of aileron-wheel force, are required for sideslip angles which might be experienced by the operational vehicle in service employment. The corresponding limits for Level 2 shall be 75 percent and 10 pounds of aileron-stick force or 20 pounds of aileron-wheel force. For the experimental vehicle, Levels 1 and 2, positive effective dihedral shall never be so great that more than 75 percent of the roll control power available to the pilot and no more than 20 pounds of aileron-stick force or 40 pounds of aileron-wheel force are required for sideslip angles which might be experienced in service employment.

3.3.7 Lateral-directional control in crosswinds. It shall be possible to take off and land with normal pilot skill and technique in 90 degree crosswinds, from either side, of velocities up to those specified in table XII. Aileron control forces shall be within the limits specified in 3.3.4.2, and rudder pedal forces shall not exceed 100 pounds for Level 1 nor 180 pounds for Levels 2 and 3. This requirement can normally be met through compliance with 3.3.7.1 and 3.3.7.2.

TABLE XII. Crosswind Velocity

Level	Crosswind	
	Operational Vehicle	Experimental Vehicle
1 & 2	30 knots	10 knots
3	15 knots	0

3.3.7.1 Final approach in crosswinds. For all operational vehicles except vehicles equipped with crosswind landing gear, or otherwise constructed to land in a large crabbed attitude, rudder- and aileron-control power shall be adequate to develop at least 10 degrees of sideslip or the sideslip specified in 3.3.6, whichever is less, with rudder pedal forces not exceeding the values specified in 3.3.7. For Level 1, aileron control shall not exceed either 7.5 pounds of force or 50 percent of control power available to the pilot. For Level 2 the corresponding limits are 10 pounds or 75 percent. The aileron control force shall not exceed 20 pounds for Level 3. For Levels 1 and 2, the experimental vehicle shall develop at least 5 degrees of sideslip or the sideslip specified in 3.3.6, whichever is less, with rudder pedal forces not exceeding the values specified in 3.3.7. For the experimental vehicle, Levels 1 and 2, aileron control shall not exceed either 20 pounds of force or 75 percent of the roll control power available to the pilot.

3.3.7.2 Takeoff run and landing rollout in crosswinds. Rudder and aileron control, in conjunction with other normal means of control, shall be adequate to maintain a straight path on the ground or other landing surface in calm air and in crosswinds up to the values specified in table XII. This requirement applies with forces not exceeding the values specified in 3.3.7.

3.3.7.2.1 Cold- and wet-weather operation. The requirements of 3.3.7.2 apply on wet runways for all operational vehicles, and on snow-packed and icy runways for operational vehicles intended to operate under such conditions. If compliance is not demonstrated under these adverse runway conditions, directional control shall be maintained by use of aerodynamic controls alone at all airspeeds above 50 knots for Class IV-0 and above 30 knots for Class III-0. For very slippery runways, the requirements need not apply for crosswind

components at which the force tending to blow the operational vehicle off the runway exceeds the opposing tire-runway frictional force with the tires supporting all of the vehicle's weight.

3.3.7.3 Taxiing wind speed limits. It shall be possible to taxi an operational vehicle at any angle in a 45-knot wind.

3.3.8 Lateral-directional control in dives. Rudder and aileron control power shall be adequate to maintain wings level and sideslip zero, without retrimming, throughout the dive and pullouts of 3.2.3.5 and 3.2.3.6. In the Service Flight Envelope, aileron control forces shall not exceed 10 pounds and rudder pedal forces shall not exceed 50 pounds.

3.3.9 Lateral-directional control with asymmetric thrust. A powered vehicle shall be safely controllable with asymmetric loss of thrust from any factor. The requirements of 3.3.9.1 through 3.3.9.4 apply for the appropriate Flight Phases when any single failure or malperformance of the propulsive system, including inability to get an air start, causes the absence or loss of thrust of one or more engines. The effect of the failure or malperformance on all subsystems powered or driven by the failed propulsive system should also be considered.

3.3.9.1 Thrust loss during takeoff run. It shall be possible for the pilot to maintain control of a powered vehicle on the takeoff surface following sudden loss of thrust from the most critical factor. Thereafter, it shall be possible to achieve and maintain a straight path on the takeoff surface without a deviation of more than 30 feet from the path originally intended, with rudder pedal forces not exceeding 180 pounds. For the continued takeoff, the requirement shall be met when thrust is lost at speeds from the refusal speed (based on the shortest runway from which the vehicle is designed to operate) to the maximum takeoff speed, with takeoff thrust maintained on the operative engine(s), using only elevator, aileron, and rudder controls. For the aborted takeoff, the requirement shall be met at all speeds below the maximum takeoff speed; however, additional controls such as nose-wheel steering and differential braking may be used. Automatic devices which normally operate in the event of a thrust failure may be used in either case.

3.3.9.2 Thrust loss after takeoff. During takeoff, it shall be possible without a change in selected configuration for the pilot to achieve straight flight following sudden asymmetric loss of thrust from the most critical factor at speeds from $V_{min}(TO)$ to $V_{max}(TO)$, and thereafter to maintain straight flight throughout the climbout. The rudder pedal force required to maintain straight flight with asymmetric thrust shall not exceed 180 pounds. Aileron control shall not exceed either the force limits specified in 3.3.4.2 or 75 percent of available control power, with takeoff thrust maintained on the operative engine(s) and trim at normal settings for takeoff with symmetric thrust. Automatic devices which normally operate in the event of a thrust failure may be used, and the vehicle may be banked up to 5 degrees away from the inoperative engine.

3.3.9.3 Transient effects. The vehicle motions following sudden asymmetric loss of thrust shall be such that dangerous conditions can be avoided by pilot corrective action. A realistic time delay (3.4.9) of at least 1 second shall be considered.

3.3.9.4 Asymmetric thrust - rudder pedals free. The static directional stability shall be such that at all speeds above $1.4V_{min}$, with asymmetric loss of thrust from the most critical factor while the other engine(s) develop normal rated thrust, the operational vehicle with rudder pedals free may be balanced directionally in steady straight flight. The trim settings shall be those required for wings-level straight flight prior to the failure. Aileron control forces shall not exceed the Level 2 limits specified in 3.3.4.2 for Levels 1 and 2 and shall not exceed the Level 3 limits for Level 3.

3.3.9.5 Two engines inoperative. With any engine inoperative, it shall be possible upon failure or the inability to get an air start of the most critical remaining engine to stop the transient motion. Furthermore, it shall be possible to maintain straight flight from the one-engine-out speed for maximum range to the speed for maximum range with both engines inoperative. In addition, it shall be possible to effect a safe recovery at any service speed above V_{0min} (CL) following sudden simultaneous failure of the two critical failing engines.

3.4 Miscellaneous flying qualities.

3.4.1 Approach to dangerous flight conditions. Dangerous conditions may exist where the vehicle should not be flown. When approaching these flight conditions, it shall be possible by clearly discernible means for the pilot to recognize the impending dangers and take preventive action. Final determination of the adequacy of all warning of impending dangerous flight conditions will be made by the procuring activity, considering functional effectiveness, whether the vehicle is operational or experimental, and the reliability required as determined by the vehicle mission. Devices may be used to prevent entry to dangerous conditions only if the criteria for their design, and the specific devices, are approved by the procuring activity.

3.4.1.1 Warning and indication. Warning or indication of approach to a dangerous condition shall be clear and unambiguous. For example, a pilot must be able to distinguish readily among stall warning (which requires pitch down or increasing speed), excessive sink rate (which requires a decrease in angle of attack), Mach buffet (which may indicate a need to decrease speed), and normal vehicle vibration (which indicates no need for pilot action). If a warning or indication device is required, functional failure of the device shall be indicated to the pilot.

3.4.1.2 Prevention. As a minimum, dangerous-condition-prevention devices shall perform their function whenever needed, but shall not limit flight within the Operational Flight Envelope. Hazardous operation, normal or inadvertent, shall never be possible. For an operational vehicle, for Levels 1 and 2, neither hazardous nor nuisance operation shall be possible.

3.4.2 Stalls. The requirements of 3.4.2 through 3.4.2.4.1 are to assure that the airflow separation induced by high angle of attack, which causes loss of aerodynamic lift or control about any one axis, does not result in a dangerous or mission-limiting condition. When the maximum angle of attack and minimum speed are limited by other considerations than stall, any or all the requirements of 3.4.2 through 3.4.2.4.1 may be waived with the prior approval of the procuring activity.

3.4.2.1 Required conditions. The requirements for stall characteristics apply for all Vehicle Normal States in straight unaccelerated flight, turns including gliding and climbing turns, and pullups with normal acceleration up to $n_{o\max}$. The requirements shall also apply to Vehicle Failure States that affect stall characteristics.

3.4.2.2 Stall warning requirements. The stall approach shall be accompanied by an easily perceptible warning. Acceptable stall warning may consist of shaking of the cockpit controls, buffeting or shaking of the vehicle, or a combination of both. The onset of this warning shall occur within the ranges specified in 3.4.2.2.1 and 3.4.2.2.2 but not within the Operational Flight Envelope. The increase in buffet intensity with further increase in angle of attack shall be sufficiently marked to be noted by the pilot. The warning may be provided artificially only if it can be shown that natural stall warning is not feasible. These requirements apply whether V_S is as defined in 6.2.2 or as allowed in 3.1.9.2.1.

Stall warning may not be required for certain Flight Phases since the vehicle may never exhibit stall characteristics or approach the stall. However, in lieu of stall warning a limiting angle of attack or some other warning may be necessary to indicate the approach to a dangerous flight condition. The Flight Phases exempted, and the type of warning used in lieu of stall warning, will be established with the approval of the procuring activity.

3.4.2.2.1 Warning speed for stalls at $1\ g\ \cos\ \gamma$ normal to the flight path. Warning onset for powered or unpowered vehicles for stalls at $1\ g\ \cos\ \gamma$ normal to the flight path shall occur between the following limits:

<u>Flight Phase</u>	<u>Minimum Stall Warning Speed</u>	<u>Maximum Stall Warning Speed</u>
C	Higher of $1.05\ V_S$ or $V_S + 5\ \text{knots}$	Higher of $1.10\ V_S$ or $V_S + 10\ \text{knots}$
A & B	Higher of $1.05\ V_S$ or $V_S + 5\ \text{knots}$	Higher of $1.15\ V_S$ or $V_S + 15\ \text{knots}$

3.4.2.2.2 Warning range for accelerated stalls. Onset of stall warning shall occur outside the Operational Flight Envelope associated with the Vehicle Normal State and within the following angle-of-attack ranges:

Flight Phase	Minimum Stall Warning Angle of Attack	Maximum Stall ¹ Warning Angle of Attack
C	$\alpha_o + 0.82(\alpha_s - \alpha_o)$	$\alpha_s + 0.90(\alpha_s - \alpha_o)$
A & B	$\alpha_o + 0.75(\alpha_s - \alpha_o)$	$\alpha_s + 0.90(\alpha_s - \alpha_o)$

where α_s is the stall angle of attack and α_o is the angle of attack for zero lift (α_o may be estimated from wind-tunnel tests or flight tests).

3.4.2.3 Stall characteristics. In the unaccelerated stalls of 3.4.2.1, the vehicle shall not exhibit uncontrollable rolling, yawing, or downward pitching at the stall in excess of 20 degrees for Class III, or 30 degrees for Class IV vehicles. It is desired that no pitch-up tendencies occur in unaccelerated or accelerated stalls. In unaccelerated stalls, mild nose-up pitch may be acceptable if no elevator control force reversal occurs and if no dangerous, unrecoverable, or objectional flight condition results. A mild nose-up tendency may be acceptable in accelerated stalls if the operational effectiveness of the airplane is not compromised and:

- The vehicle has adequate stall warning
- Elevator effectiveness is such that it is possible to stop the pitch-up promptly and reduce the angle of attack, and
- At no point during the stall, stall approach, or recovery does any portion of the vehicle exceed structural limit loads.

The requirements apply to all stalls resulting from rates of speed reduction up to 4 knots per second. The stall characteristics will be considered unacceptable if a spin is likely to result.

3.4.2.4 Stall recovery and prevention. It shall be possible to prevent the complete stall by moderate use of the controls at the onset of the stall warning. It shall be possible to recover from a complete stall by use of the elevator, aileron, and rudder controls with reasonable forces, and to regain level flight for a powered vehicle and steady-state glide flight for an unpowered vehicle. Such recovery shall be possible without excessive loss of altitude or buildup of speed. For a powered vehicle, throttle shall remain fixed until speed has begun to increase when an angle of attack below the stall has been regained. In the straight-flight stalls of 3.4.2.1, with the vehicle trimmed at a speed not greater than $1.4 V_S$ and with a speed reduction rate of at least 4.0 knots per second, elevator control power shall be sufficient to recover from any attainable angle of attack.

3.4.2.4.1 One-engine-out stalls. On multi-engine vehicles in cruise flight, it shall be possible to recover safely from stalls with the critical engine inoperative. This requirement applies with the remaining engines at up to thrust for level flight at $1.4 V_S$, but these engines may be throttled back during recovery.

3.4.3 Spin recovery. If spin demonstration is required by MIL-S-25015 or MIL-D-8708 (with any modifications to make them applicable to lifting re-entry vehicles), consistent prompt recoveries shall be possible from all modes of incipient and fully developed erect and inverted spins, using controls as required by the referenced specifications. If such controls include a special spin recovery device, that device shall satisfy the following additional requirements: required pilot action shall be easy, consistent, and simple; the device shall be immediately reusable for several spins on the same flight. Recovery control forces shall not exceed 250 pounds rudder, 75 pounds elevator, or 35 pounds aileron.

3.4.4 Roll-pitch-yaw coupling. For Class III and Class IV vehicles in rudder-pedal free, elevator-control-fixed, maximum-performance rolls through 90 degrees, entered from straight flight or gliding flight, or from turns, gliding turns, pushovers, or pullups ranging from 0 g to 0.8 $\frac{1}{4}$, the resulting yawing or pitching motion and sideslip or angle-of-attack changes shall neither exceed structural limits nor cause other dangerous flight conditions such as uncontrollable motions or roll autorotation. These requirements define Level 1 and Level 2 operation.

3.4.5 Control harmony. The elevator and aileron force and displacement sensitivities and breakout forces shall be compatible so that intentional inputs to one control axis will not cause inadvertent inputs to the other.

3.4.5.1 Control force coordination. The cockpit control forces required to perform maneuvers which are normal for the vehicle should have magnitudes which are related to the pilot's capability to produce such forces in combination. The following control force levels are considered to be limiting values compatible with the pilot's capability to apply simultaneous forces:

<u>Type Control</u>	<u>Elevator</u>	<u>Aileron</u>	<u>Rudder</u>
Center-stick	50 pounds	25 pounds	175 pounds
Wheel	75 pounds	40 pounds	175 pounds

3.4.6 Buffet. Within the boundaries of the Operational Flight Envelope, there shall be no objectionable buffet which might detract from the effectiveness of the vehicle in executing its intended missions.

3.4.7 Release of stores. The intentional release of any stores shall not result in objectionable flight characteristics for Levels 1 and 2. However, the intentional release of stores shall never result in dangerous or intolerable flight characteristics. This requirement applies for all flight conditions and store loadings at which normal or emergency store release is structurally permissible.

3.4.8 Effects of special equipment. Operation of movable parts such as cargo doors, refueling devices, rescue equipment, or delivery or pickup of cargo shall not cause buffet, trim changes, or other characteristics which impair the tactical effectiveness of the vehicle under any pertinent flight condition. These requirements shall be met for Levels 1 and 2.

3.4.9 Transients following failures. The vehicle motions following sudden vehicle system or component failures shall be such that dangerous conditions can be avoided by pilot corrective action. A realistic time delay between the failure and initiation of pilot corrective action shall be incorporated when determining compliance. This time delay should include an interval between the occurrence of the failure and the occurrence of a cue such as acceleration, rate, displacement, or sound that will definitely indicate to the pilot that a failure has occurred, plus an additional interval which represents the time required for the pilot to diagnose the situation and initiate corrective action.

3.4.10 Failures. No single failure of any component or system shall result in dangerous or intolerable flying qualities; Special Failure States (3.1.6.2.1) are excepted. The crew member concerned shall be provided with immediate and easily interpreted indications whenever failures occur that require or limit any crew action or decision.

3.5 Characteristics of the primary flight control system.

3.5.1 General characteristics. As used in this specification, the term primary flight control system includes the elevator, aileron, and rudder controls (including control surface interconnects), stability augmentation system, and all mechanisms and devices that they operate. The requirements of this section are concerned with those aspects of the primary flight control system which are directly related to flying qualities. These requirements are in addition to the requirements of the applicable control system design specification, e.g., MIL-F-9490 or MIL-C-18244.

3.5.2 Mechanical characteristics. Some of the important mechanical characteristics of control systems (including servo valves and actuators) are: friction and preload, lost motion, flexibility, mass imbalance and inertia, non-linear gearing, and rate limiting. Requirements for these characteristics are contained in 3.5.2.1 through 3.5.2.4. Meeting these separate requirements, however, will not necessarily ensure that the overall system will be satisfactory; the mechanical characteristics must be compatible with the nonmechanical portions of the control system and with the airframe dynamic characteristics.

3.5.2.1 Control centering and breakout forces. Longitudinal, lateral, and directional controls should exhibit positive centering in flight at any normal trim setting. Although absolute centering is not required, the combined effects of centering, breakout force, stability, and force gradient shall not produce objectionable flight characteristics, such as poor precision-tracking ability, or permit large departures from trim conditions with controls free. Breakout forces, including friction, preload, etc., shall be within the limits of table XIII. The values in table XIII refer to the cockpit control force required to start movement of the control surface in flight for Levels 1 and 2; the upper limits are doubled for Level 3.

3.5.2.2 Cockpit control free play. The free play in each cockpit control, that is, any motion of the cockpit control which does not move the control surface in flight, shall not result in objectionable flight characteristics, particularly for small-amplitude control inputs.

TABLE XIII. Allowable Breakout Forces, Pounds

		Class IV		Class III	
		Min	Max	Min	Max
Elevator	Stick	1/2	3	1/2	5
	Wheel	1/2	4	1/2	7
Aileron	Stick	1/2	2	1/2	4
	Wheel	1/2	3	1/2	6
Rudder		1	7	1	14

3.5.2.3 Rate of control displacement. The ability of the vehicle to perform the operational maneuvers required of it shall not be limited in the atmospheric disturbances specified in 3.7 by control surface deflection rates. For powered or boosted controls, the effect of engine speed and the duty cycle of both primary and secondary controls together with the pilot control techniques shall be included when establishing compliance with this requirement.

3.5.2.4 Adjustable controls. When a cockpit control is adjustable for pilot physical dimensions or comfort, the control forces defined in 6.2 refer to the mean adjustment. A force referred to any other adjustment shall not differ by more than 10 percent from the force referred to the mean adjustment.

3.5.3 Dynamic characteristics. The response of the control surfaces in flight shall not lag the cockpit control force inputs by more than the angles shown in table XIV, for frequencies equal to or less than the frequencies shown in table XIV.

TABLE XIV. Allowable Control Surface Lags

Level	Allowable Lag - Deg.		Control	Upper Frequency rad/sec
	Category C Flight Phase	Category A & B Flight Phase		
1 & 2	30	45	Elevator	ω_{nsp}
3	60		Rudder & Aileron	ω_{nd} or $1/\tau_R$ (whichever is larger)

The lags referred to are the phase angles obtained from steady-state frequency responses, for reasonably large-amplitude force inputs. The lags for very small control-force amplitudes shall be small enough that they do not interfere with the pilot's ability to perform any precision tasks required in normal operation.

Alternate methods of defining acceptable dynamic characteristics or the magnitude of control surface lags and frequencies at which the lags should be determined may be used by the contractor provided substantiating data is supplied to, and approval is obtained from the procuring activity.

3.5.3.1 Control feel. In flight, the cockpit-control deflection shall not lead the cockpit-control force for any frequency or force amplitude. This requirement applies to the elevator, aileron, and rudder controls. In flight, the cockpit-control deflection shall not lag the cockpit control force by more than the angles listed in 3.5.3, for frequencies equal to or less than those listed in 3.5.3, for reasonably large force inputs. The lags for very small control-force amplitudes shall not interfere with the pilot's ability to perform precision tasks required in normal operation.

3.5.3.2 Damping. All control system oscillations shall be well damped, unless they are of such an amplitude, frequency, and phasing that they do not result in objectionable oscillations of the cockpit controls or the airframe during abrupt maneuvers and during flight in the atmospheric disturbances specified in 3.7.3 and 3.7.4.

3.5.4 Augmentation systems. Normal operation of stability augmentation and control augmentation systems and devices shall not introduce any objectionable flight or ground handling characteristics.

3.5.4.1 Performance of augmentation systems. Performance degradation of augmentation systems caused by atmospheric disturbances, limit cycle, and coupling due to structural vibrations and structural modes, shall be considered when such systems are used. When considering atmospheric disturbances, the disturbance of 3.7.3 and 3.7.4 should prevail.

3.5.4.2 Saturation of augmentation systems. Limits on the authority of the augmentation systems, or saturation of equipment shall not result in objectionable flying qualities. In particular, this requirement shall be met during rapid large-amplitude maneuvers, during operation near V_S , and during flight in the atmospheric disturbances of 3.7.3 and 3.7.4.

3.5.5 Failures. If the flying qualities with any or all of the augmentation devices inoperative are dangerous or intolerable, special provisions shall be incorporated to preclude a critical single failure. Failure-induced transient motions and trim changes resulting either immediately after failure or upon subsequent transfer to alternate control modes shall be small and gradual enough that dangerous flying qualities never result.

3.5.5.1 Failure transients. With controls free, the vehicle motions due to failures described in 3.5.5 shall not exceed the following limits for at least 2 seconds following the failure, as a function of the Level of flying qualities after the failure transient has subsided:

Level 1 (after failure)	± 0.1 g normal or lateral acceleration at the pilot's station and ± 1 degree per second in roll
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Level 2 (after failure)	± 0.5 g at the pilot's station, ± 5 degrees per second roll, and the lesser of ± 5 degrees sideslip or the structural limits.
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Level 3 (after failure)	No dangerous attitude or structural limit is reached, and no dangerous alteration of the flight path results from which recovery is impossible.
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3.5.5.2 Trim changes due to failures. The change in control forces required to maintain attitude and sideslip for the failures described in 3.5.5 shall not exceed the following limits for at least 5 seconds following the failure:

Elevator -----	20 pounds
Aileron -----	10 pounds
Rudder -----	50 pounds

3.5.6 Transfer to alternate control modes. The transient motions and trim changes resulting from the intentional engagement and disengagement of any portion of the primary flight control system by the pilot shall be small and gradual enough that dangerous flying qualities never result.

3.5.6.1 Transients. With controls free, the transients resulting from the situations described in 3.5.6 shall not exceed the following limits for at least 2 seconds following the transfer:

Within the Operational Flight Envelope	± 0.1 g normal or lateral acceleration at the pilot's station and ± 1 degree per second roll
Within the Service Flight Envelope	± 0.5 g at the pilot's station, ± 5 degrees per second roll, and the lesser of ± 5 degrees sideslip or the structural limit

These requirements apply only for Vehicle Normal States.

3.5.6.2 Trim changes. The change in control forces required to maintain attitude and sideslip for the situations described in 3.5.6 shall not exceed the following limits for at least 5 seconds following the transfer:

Elevator	-----	20 pounds
Aileron	-----	10 pounds
Rudder	-----	50 pounds

These requirements apply only for Vehicle Normal States.

3.6 Characteristics of secondary control systems.

3.6.1 Trim system. In straight flight, throughout the Operational Flight Envelope the trimming devices shall be capable of reducing the elevator, rudder, and aileron control forces to zero for Levels 1 and 2. For Level 3, the untrimmed cockpit control forces shall not exceed 10 pounds elevator, 5 pounds aileron, and 20 pounds rudder. The failures to be considered in applying the Level 2 and 3 requirements shall include trim sticking and runaway in either direction. It is permissible to meet the Level 2 and Level 3 requirements by providing the pilot with alternate trim mechanisms or override capability. Additional requirements on trim rate and authority are contained in MIL-F-9490 and MIL-F-18372.

3.6.1.1 Trim for asymmetric thrust. For all multi-engine vehicles, it shall be possible to trim the elevator, rudder, and aileron control forces to zero in straight flight with up to two engines inoperative following asymmetric loss of thrust from the most critical factors (3.3.9). This requirement defines Level 1 in level-flight cruise of speeds from the maximum range speed for the engine(s)-out configuration to the speed obtainable with normal rated thrust on the remaining engine(s). Systems completely dependent on the failed engines shall also be considered failed.

3.6.1.2 Rate of trim operation. Trim devices shall operate rapidly enough to enable the pilot to maintain low control forces under changing conditions normally encountered in service, yet not so rapidly as to cause oversensitivity or trim precision difficulties under any conditions. Specifically, it shall be possible to trim the elevator control forces to less than ± 10 pounds for center-stick vehicles and ± 20 pounds for wheel-controlled vehicles throughout: (a) moderate dives, unpowered or powered glides, angle-of-attack transitions, and other maneuvers that may be required in normal service operation, and (b) level-flight accelerations at maximum thrust from 250 knots or V_R/C , whichever is less to V_{max} at any altitude when the vehicle is trimmed for level flight prior to initiation of the maneuver.

3.6.1.3 Stalling of trim systems. Stalling of a trim system due to aerodynamic loads during maneuvers shall not result in an unsafe condition. Specifically, the longitudinal trim system shall be capable of operating during the dive recoveries of 3.2.3.6 at any attainable permissible n , at any possible position of the trimming device.

3.6.1.4 Trim system irreversibility. All trimming devices shall maintain a given setting indefinitely, unless changed by the pilot, by a special automatic interconnect such as to the landing flaps, or by the operation of an augmenta-

tion device. If an automatic interconnect or augmentation device is used in conjunction with a trim device, provision shall be made to ensure the accurate return of the device to its initial trim position on completion of each interconnect or augmentation operation.

3.6.2 Speed and flight-path control devices. The effectiveness and response times of the fore- and aft-force controls, in combination with the other longitudinal controls, shall be sufficient to provide adequate control of flight path and airspeed at any flight condition within the Operational Flight Envelope. This requirement may be met by use of devices such as throttles, thrust reversers, auxiliary drag devices, and flaps. For an unpowered vehicle in the landing approach, an auxiliary drag device shall be provided that is easily and continuously controllable by the pilot from its retracted to fully extended position. The drag should vary reasonably linearly with extension, and when fully extended it must be capable of at least doubling the drag of the vehicle during an equilibrium glide at a speed for minimum drag. The minimum drag and speed for minimum drag are defined for the vehicle with speed and flight path control devices used during the landing approach, including landing gear, retracted.

3.6.3 Transient and trim changes. The transients and steady-state trim changes for normal operation of secondary control devices (such as throttle, flaps, slats, speed brakes, deceleration devices, dive recovery devices, wing sweep, and landing gear) shall not impose excessive control forces to maintain the desired heading, altitude, attitude, rate of climb, speed or load factor without use of the trimmer control. This requirement applies to all in-flight configuration changes and combinations of changes made under service conditions, including the effects of asymmetric operations such as unequal operation of landing gear, speed brakes, slats, or flaps. In no case shall there be any objectionable buffeting or oscillation of such devices. More specific requirements on secondary control devices are contained in 3.6.3.1, 3.6.4, and 3.6.5 and in MIL-F-9490 and MIL-F-18372.

3.6.3.1 Pitch trim changes. The pitch trim changes caused by operation of secondary control devices shall not be so large that a peak elevator control force in excess of 10 pounds for center-stick controllers or 20 pounds for wheel controllers is required when such configuration changes are made in flight under conditions representative of operational procedure. Conditions will be established by the procuring activity for determination of compliance with this requirement. With the vehicle trimmed for each specified initial condition, the peak force required to maintain the specified parameter constant following the specified configuration change shall not exceed the stated value for a time interval of at least 5 seconds following the completion of the pilot action initiating the configuration change. The magnitude and rate of trim change subsequent to this time period shall be such that the forces are easily trimmable by use of the normal trimming devices. These requirements define Level 1. For Levels 2 and 3, the allowable forces are increased by 50 percent.

3.6.4 Auxiliary dive recovery devices. Operation of any auxiliary device intended solely for dive recovery shall always produce a positive increment of normal acceleration, but the total normal load factor shall never exceed 0.8 n_L , controls free.

3.6.5 Direct normal-force control. Use of devices for direct normal-force control shall not produce objectionable changes in attitude for any amount of control up to the maximum available. This requirement shall be met for Levels 1 and 2.

3.7 Atmospheric disturbances.

3.7.1 Use of turbulence models. Paragraphs 3.7.2 through 3.7.5 specify continuous turbulence models and a discrete turbulence model that shall be used in analyses to determine compliance with those requirements of this specification that refer to 3.7 explicitly, to assess:

- a. The effect of turbulence on the flying qualities of the vehicle
- b. The ability of a pilot to recover from the effects of discrete gusts

3.7.2 Turbulence models. Where feasible, the von Karman form shall be used for the continuous random turbulence model, so that the flying qualities analyses will be consistent with the comparable structural analyses. When no comparable structural analysis is performed or when it is not feasible to use the von Karman form, use of the Dryden form will be permissible. In general, both the continuous random model and the discrete model shall be used. At the request of the procuring activity, the contractor may be required to use a continuous non-Gaussian model for one or more of the turbulence velocities in lieu of the models defined in 3.7.2.1 and 3.7.2.2. The scales and intensities used in determining the gust magnitudes for the discrete model shall be the same as those used in the continuous random model.

3.7.2.1 Continuous random model (von Karman form). The von Karman form of the spectra for the turbulence velocities is:

$$\begin{aligned}\bar{\Phi}_{u_g}(\Omega) &= \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{[1 + (1.339L_u\Omega)^2]^{5/6}} \\ \bar{\Phi}_{v_g}(\Omega) &= \sigma_v^2 \frac{L_v}{\pi} \frac{1 + \frac{8}{3}(1.339L_v\Omega)^2}{[1 + (1.339L_v\Omega)^2]^{11/6}} \\ \bar{\Phi}_{w_g}(\Omega) &= \sigma_w^2 \frac{L_w}{\pi} \frac{1 + \frac{9}{3}(1.339L_w\Omega)^2}{[1 + (1.339L_w\Omega)^2]^{11/6}}\end{aligned}$$

3.7.2.2 Continuous random model (Dryden form). The Dryden form of the spectra for the turbulence velocities is:

$$\bar{\Phi}_{u_g}(\Omega) = \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{1 + (L_u \Omega)^2}$$

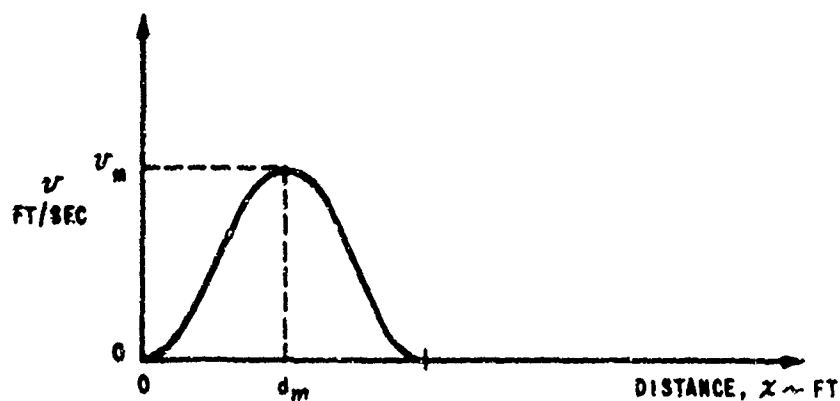
$$\bar{\Phi}_{v_g}(\Omega) = \sigma_v^2 \frac{L_v}{\pi} \frac{1 + 3(L_v \Omega)^2}{[1 + (L_v \Omega)^2]^2}$$

$$\bar{\Phi}_{w_g}(\Omega) = \sigma_w^2 \frac{L_w}{\pi} \frac{1 + 3(L_w \Omega)^2}{[1 + (L_w \Omega)^2]^2}$$

3.7.2.3 Non-Gaussian models (von Karman or Dryden form). The contractor may be required to use a non-Gaussian model for one or more of the turbulence velocities when such representation seems advisable for a more realistic simulation of turbulence, especially at lower altitudes. Non-Gaussian models may be especially advisable for vehicles with large roll acceleration due to sideslip. The turbulence model in such cases will be selected by consultation between the contractor and the procuring activity.

3.7.2.4 Discrete model. The discrete turbulence model may be used for any of the three gust-velocity components. The discrete gust has the "1 - cosine" shape:

$$\begin{aligned} v &= 0 & , x < 0 \\ &= \frac{v_m}{2} \left(1 - \cos \frac{\pi x}{d_m} \right) & , 0 \leq x \leq 2d_m \\ &= 0 & , x > 2d_m \end{aligned}$$



Several values of d_m shall be used, each chosen so that the gust is tuned to each of the natural frequencies of the vehicle and its flight control system (higher-frequency structural modes may be expected). The magnitude v_m shall then be chosen from figure 7. The parameters L and σ to be used with figure 7 are the Dryden scales and intensities from 3.7.3 or 3.7.4 for the velocity component under consideration.

3.7.3 Scales and intensities (clear air turbulence). The root-mean-square intensity σ_w for clear air turbulence is defined on figure 8 as a function of altitude. The intensities σ_u and σ_v may be obtained using the relationships

$$\frac{\sigma_u^2}{L_u^{2/3}} = \frac{\sigma_v^2}{L_v^{2/3}} = \frac{\sigma_w^2}{L_w^{2/3}} \quad (\text{von Karman form})$$

$$\frac{\sigma_u^2}{L_u} = \frac{\sigma_v^2}{L_v} = \frac{\sigma_w^2}{L_w} \quad (\text{Dryden form})$$

The root-mean-square intensity σ for clear air turbulence as defined on figure 8 may be reduced for an experimental vehicle. The degree of reduction will be determined by consultation between the contractor and the procuring activity.

The scales for clear air turbulence are defined in 3.7.3.1 and 3.7.3.2 as a function of altitude. The altitude shall be defined consistently with any applicable terrain models specified in the contract. For those Flight Phases involving climbs and descents, a single set of scales and intensities based on an average altitude may be used. If an average set of scales and intensities is used for Category C Flight Phases, it shall be based on an altitude of 500 feet.

3.7.3.1 Clear air turbulence (von Karman scales). The scales for clear air turbulence using the von Karman form are:

Above $h = 2500$ feet: $L_u = L_v = L_w = 2500$ feet

Below $h = 2500$ feet: $L_w = h$ feet

$$L_u = L_v = 184 h^{1/3} \text{ feet}$$

3.7.3.2 Clear air turbulence (Dryden scales). The scales for clear air turbulence using the Dryden form are:

Above $h = 1750$ feet: $L_u = L_v = L_w = 1750$ feet

Below $h = 1750$ feet: $L_w = h$ feet

$$L_u = L_v = 145 h^{1/3} \text{ feet}$$

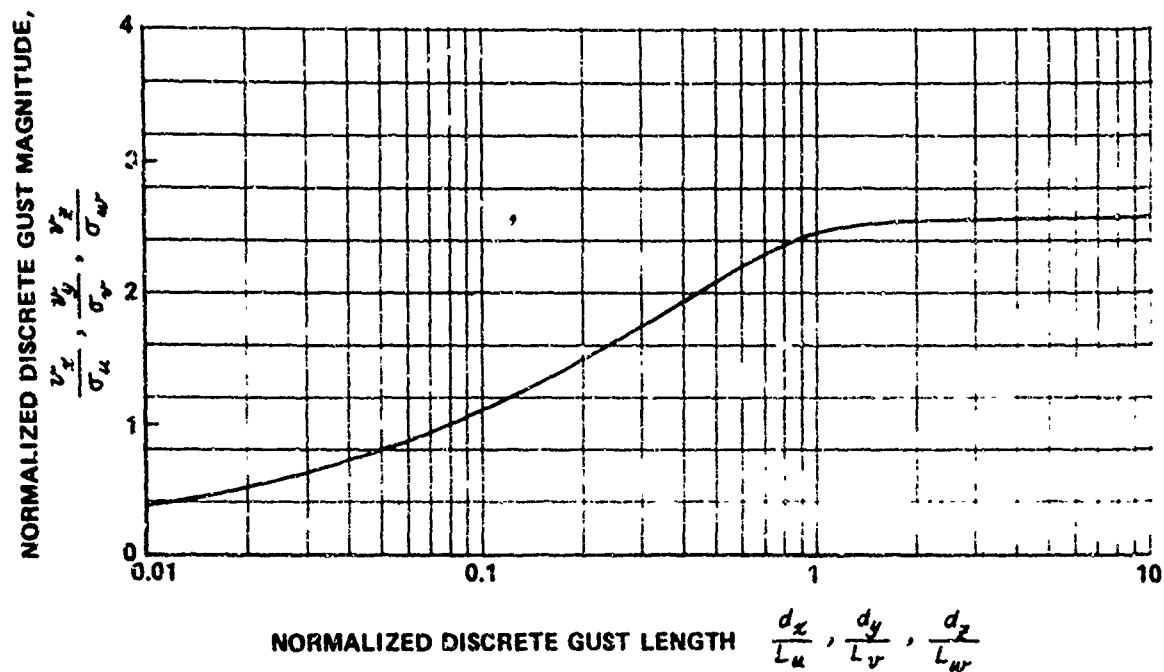


Figure 7 MAGNITUDE OF DISCRETE GUSTS

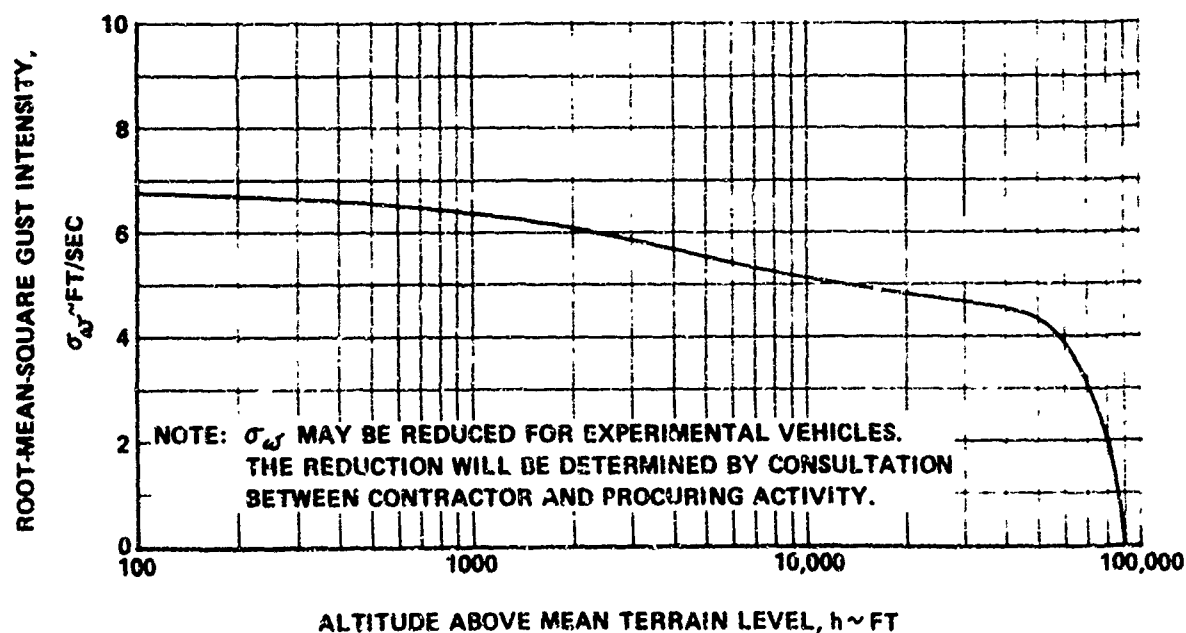


Figure 8 INTENSITY FOR CLEAR AIR TURBULENCE

3.7.4 Scales and intensities (thunderstorm turbulence). The root-mean-square intensities σ_u , σ_v , and σ_w are all equal to 21 feet per second for thunderstorm turbulence. The scales for thunderstorm turbulence are defined in 3.7.4.1 and 3.7.4.2. These values are to be used when evaluating the airplane's controllability in severe turbulence, but need not be considered for altitudes above 40,000 feet.

Thunderstorm turbulence is not a consideration for Class III (E) and IV (E) vehicles.

3.7.4.1 Thunderstorm turbulence (von Karman scales). The scales for thunderstorm turbulence using the von Karman form are $L_u = L_v = L_w = 2500$ feet.

3.7.4.2 Thunderstorm turbulence (Dryden scales). The scales for thunderstorm turbulence using the Dryden form are $L_u = L_v = L_w = 1750$ feet.

3.7.5 Application of the turbulence models in analysis. The gust velocities shall be applied to the vehicle equations of motion through the aerodynamic terms only, and the direct effect of the gust on the aerodynamic sensors shall be included when such sensors are part of the vehicle augmentation system. When using the discrete model, all significant aspects of the penetration of the gust by the vehicle shall be incorporated in the analyses. Application of the continuous random model or the continuous non-Gaussian model depends on the range of frequencies of concern in the analyses of the airframe. When structural modes are significant, the exact distribution of the gust velocities over the airframe should be considered. For this purpose, it is acceptable to consider u_g and v_g as being one-dimensional functions only of x , but w_g shall be considered two-dimensional, a function of both x and y , for the evaluation of aerodynamic forces and moments. When structural modes are not significant, airframe rigid-body responses may be evaluated by considering uniform gust immersion along with linear gradients of the gust velocities. The uniform immersion is accounted for by u_g , v_g , and w_g defined at the vehicle center of gravity. The angular velocities due to the turbulence are equivalent in effect to the vehicle angular velocities. These angular velocities are defined (precisely at very low frequencies only) as follows:

$$p_g = - \frac{\partial w_g}{\partial y}, \quad q_g = + \frac{\partial w_g}{\partial x} = -\dot{\alpha}_g, \quad r_g = - \frac{\partial v_g}{\partial x}$$

$$\Phi_{p_g}(\Omega) = \frac{\sigma_w^2}{L_w} \frac{0.8 \left(\frac{\pi L_w}{4b} \right)^{1/3}}{1 + \left(\frac{4b}{\pi} \Omega \right)^2}$$

$$\Phi_{q_g}(\Omega) = \frac{\Omega^2}{1 + \left(\frac{4b}{\pi} \Omega\right)^2} \Phi_{w_g}(\Omega)$$

$$\Phi_{v_g}(\Omega) = \frac{\Omega^2}{1 + \left(\frac{3b}{\pi} \Omega\right)^2} \Phi_{v_g}(\Omega) \quad \text{where } b = \text{wing span}$$

The turbulence velocities u_g , v_g , w_g , p_g , q_g , and r_g are then applied to the airplane equations of motion through the aerodynamic terms. For longitudinal analyses u_g , w_g , and q_g gusts should be employed. For lateral-directional analyses v_g , p_g , and r_g should be used. The gust velocity components u_g , v_g , and w_g shall be considered mutually independent and q_g is correlated with v_g . The rolling velocity gust p_g is statistically independent of all the other gust components.

After consultation with the contractor, the procuring activity may require that a non-Gaussian gust model be used for one or more of the gust velocities in the simulation, when "patchy" turbulence may be an important consideration for lifting re-entry vehicle configurations. A simplified gust representation, such as the effects of gusts on only α and β , will be accepted when justification can be supplied by the contractor to the procuring activity that such simplification adequately accounts for the important gust effects on the vehicle flying qualities.

4. QUALITY ASSURANCE

4.1 Compliance demonstration. Quality assurance shall be determined through:

Analysis
Simulation
Ground test
Flight test

The contract end item specification for each procurement will delineate, for each requirement of Section 3, which of these methods shall be used. The extent to which compliance will be determined by flight test will be a function of the vehicle flight time or endurance during various Flight Phases. Emphasis on compliance during flight tests will be placed on vehicles and Flight Phases with adequate flight time for testing. For an unpowered vehicle, compliance with many requirements will be determined during glide and gliding turns. When speed is to be held constant, constant indicated airspeed in glides and gliding turns will be accepted in lieu of equilibrium flight at constant speed and altitude. Requirements associated with variations from one equivalent speed to another at constant altitude will be applicable (within certain altitude and attitude limitations) to glide and gliding turns from one indicated airspeed to

another. In order to restrict the number of design and test conditions, representative flight conditions, configurations, external store complements, loadings, etc., shall be determined for detailed investigation. The selected design points must be sufficient to allow accurate extrapolation to the other conditions at which the requirements apply. The required failure analysis shall be thorough except when alternate and simplified methods of accounting for failures or failure analysis are accepted and approved by the procuring activity. An additional exception is approved Special Failure States (3.1.6.2.1).

4.2 Vehicle states.

4.2.1 Weights and moments of inertia. Selected design points should include conditions of heaviest weight and greatest moment of inertia. "Heaviest weight" and "greatest moment of inertia" mean the heaviest and greatest consistent with 3.1.2 and 3.1.3. When a critical center-of-gravity position is identified, the vehicle weight and associated moments of inertia shall correspond to the most adverse service loading in which that critical center-of-gravity position is obtained.

4.2.2 Center-of-gravity positions. Selected design points should include most forward and most aft c.g. points that are consistent with 3.1.2. When a critical weight or moment of inertia is identified, the center-of-gravity position shall correspond to the most adverse service loading in which the critical weight or moment of inertia is obtained.

4.2.3 Thrust settings. When the vehicle is powered, thrust settings for selected design conditions shall be established by agreement between the procuring activity and the contractor. Similarly, nominal settings of drag devices shall be established for unpowered vehicles.

4.3 Design and test conditions.

4.3.1 Altitudes. For the terminal Flight Phases of the vehicle with an onboard propulsion system for sustained flight, it will normally suffice to examine selected Vehicle States at only one altitude below 10,000 feet (low altitude). For nonterminal Flight Phases of the vehicle with an onboard propulsion system for sustained flight, it will normally suffice to examine the selected Vehicle States at one altitude below 10,000 feet or at the lowest operational altitude (low altitude), the maximum operational altitude (h_{omax}), and one intermediate altitude. When the maximum operational altitude is above 40,000 feet or when stability or control characteristics vary rapidly with altitude, more intermediate altitudes shall be investigated. When the Service Flight Envelope extends far above or below the Operational Flight Envelope, the service-altitude extremes must be considered. For an unpowered vehicle, the terminal and non-terminal Flight Phases shall be explored at altitudes as they occur during glide and gliding turns to touchdown.

4.3.2 Special conditions. In addition to the flight conditions previously indicated, the speed-altitude combinations that result in the following shall all be investigated, where applicable and possible:

- a. Maximum normal acceleration response per degree of elevator deflection
- b. Maximum normal acceleration response per pound of stick force
- c. Highest dynamic pressure and highest Mach number
- d. Lowest dynamic pressure and lowest Mach number
- e. Highest angle of attack.
- f. Lowest angle of attack
- g. Most critical angle of attack condition as determined by mutual agreement between the contractor and procuring activity.

4.4 Interpretation of qualitative requirements. In several instances throughout the specification, qualitative terms such as "objectionable flight characteristics", "realistic time delay", and "normal pilot technique", have been employed to permit latitude where absolute quantitative criteria might be unduly restrictive, final determination of compliance with requirements so worded will be made by the procuring activity (1.5).

5. PREPARATION FOR DELIVERY

5.1 General. Not applicable to this specification.

6. NOTES

6.1 Intended use. This specification contains the handling qualities requirements for lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds and forms one of the bases for determination by the procuring activity of vehicle acceptability. The specification serves as design requirements and as criteria for use in stability and control calculations, analysis of wind-tunnel test results, flying qualities simulation tests, and flight testing and evaluation. The requirements are intended to assure adequate flying qualities regardless of design implementation or flight control system mechanization. To the extent possible, this specification should be met by providing an inherently good basic vehicle. Where that is not entirely feasible, or where inordinate penalties would result, a mechanism is provided herein to assure that the flight safety, flying qualities and reliability aspects of dependence on stability augmentation and other forms of system complication will be considered fully.

6.2 Definitions. Terms and symbols used throughout this specification are defined as follows:

6.2.1 General

Axis system	<ul style="list-style-type: none">- Unless otherwise stated, the motion, load factor and similar quantities are referred to an orthogonal body-axis system with its origin at the airplane c.g., with:- x along the projection of the undisturbed (trim or operating point) velocity onto the plane of symmetry- y perpendicular to the plane of symmetry, directed out the right wing- z completing a right-hand axis system.
S	<ul style="list-style-type: none">- Wing area
s	<ul style="list-style-type: none">- Laplace transform variable
\bar{q}	<ul style="list-style-type: none">- dynamic pressure
T_2	<ul style="list-style-type: none">- time to double amplitude; $T_2 = (-.693/\zeta\omega_n)$ for oscillations, $T_2 = -.693\tau$ for first-order divergences
h_{\max}	<ul style="list-style-type: none">- maximum service altitude (defined in 3.1.8.3)
h_{Omax}	<ul style="list-style-type: none">- maximum operational altitude (3.1.7)
h_{Omin}	<ul style="list-style-type: none">- minimum operational altitude (3.1.7)
c.g.	<ul style="list-style-type: none">- vehicle center of gravity

6.2.2 Speeds

Equivalent airspeed	<ul style="list-style-type: none">- true airspeed multiplied by $\sqrt{\sigma}$, where σ is the ratio of free-stream density at the given altitude to standard sea-level air density
Refusal speed	<ul style="list-style-type: none">- the maximum speed to which the vehicle can accelerate and then stop in the available runway length
M	<ul style="list-style-type: none">- Mach number
V	<ul style="list-style-type: none">- airspeed (where appropriate, V may be replaced by M in this specification), along the flight path
V_S	<ul style="list-style-type: none">- stall speed (equivalent airspeed), at $1g \cos \gamma$ normal to the flight path, defined as the highest of:

- a. speed for steady straight flight at $C_{L_{max}}$, the first local maximum of the curve of lift coefficient (L/qS) vs. angle of attack which occurs as C_L is increased from zero
- b. speed at which abrupt uncontrollable pitching, rolling or yawing occurs; i.e., loss of control about a single axis
- c. speed at which intolerable buffet or structural vibration is encountered

(Note that 3.1.9.2.1 allows an alternative definition of V_S in some cases)

$V_X(X)$, $V_{min}(X)$,

- short-hand notation for the speeds V_S , V_{min} , V_{max} for a given configuration, weight, center-of-gravity position, and external store combinations associated with Flight Phase X. For example, the designation $V_{max}(TO)$ is used in 3.2.3.3.2 to emphasize that the speed intended (for the weight, center of gravity, and external store combination under consideration) is V_{max} for the configuration associated with the takeoff Flight Phase. This is necessary to avoid confusion, since the configuration and Flight Phase change from takeoff to climb during the maneuver.

$V_{L/D}$

- speed for maximum lift-to-drag ratio

$V_{R/C}$

- speed for maximum rate of climb

V_{NRT}

- high speed, level flight, normal rated thrust

V_{MRT}

- high speed, level flight, military rated thrust

V_{MAT}

- high speed, level flight, maximum augmented thrust

V_{max}

- maximum service speed (defined in 3.1.8.1)

V_{min}

- minimum service speed (defined in 3.1.8.2)

V_{Omax}

- maximum operational speed (3.1.7)

V_{Omin}

- minimum operational speed (3.1.7)

6.2.3 Thrust and Boost

- NRT - normal rated thrust, which is the maximum thrust at which the engine can be operated continuously
- MRT - military rated thrust, which is the maximum thrust at which the engine can be operated for a specified period
- MAT - maximum augmented thrust; maximum thrust, augmented by all means available for the Flight Phase
- Takeoff thrust - maximum thrust available for takeoff
- Powered boost - The boost with power flight phase of a single stage experimental vehicle which occurs just after launch of the vehicle from another aircraft.

6.2.4 Control parameters

- Elevator, aileron, rudder controls - The stick or wheel and rudder pedals manipulated by the pilot to produce pitching, rolling, and yawing moment respectively; the cockpit controls
- Elevator control force - Component of applied force, exerted by the pilot on the cockpit control, in or parallel to the plane of symmetry, acting at the center of the stick grip or wheel in a direction perpendicular to a line between the center of the stick grip or wheel and the stick or control column pivot.
- Aileron control force - For a stick control, the component of control force exerted by the pilot in a plane perpendicular to the plane of symmetry, acting at the center of the stick grip in a direction perpendicular to a line between the center of the stick grip and the stick pivot.

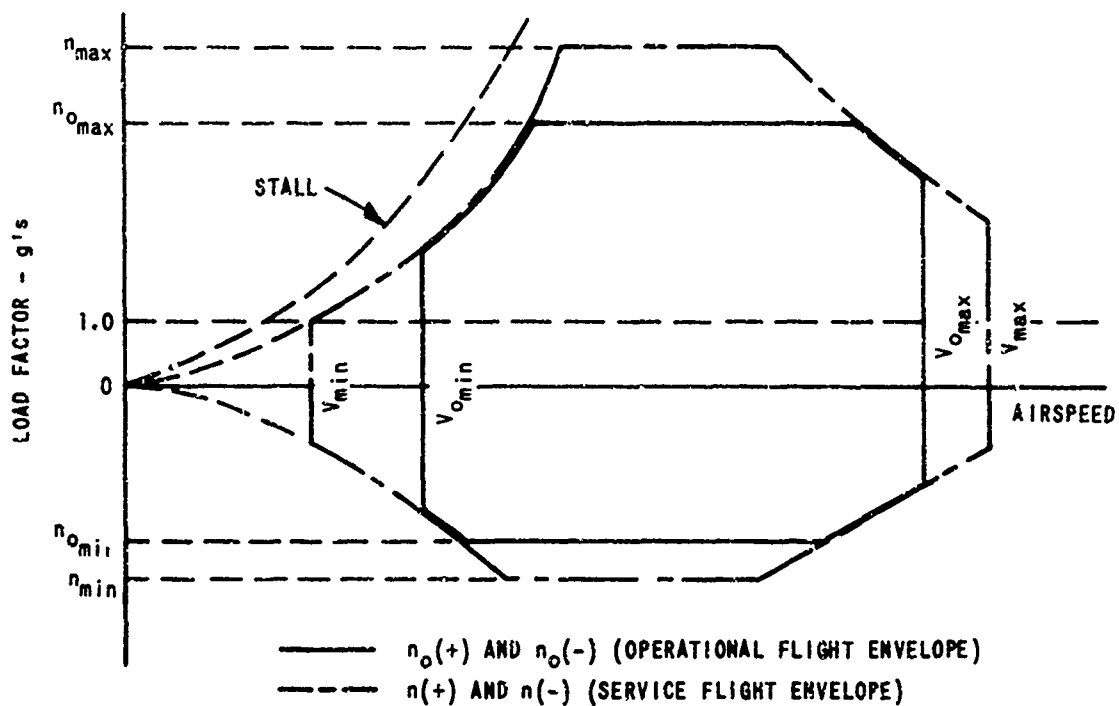
For a wheel control, the total moment applied by the pilot about the wheel axis in the plane of the wheel, divided by the average radius from the wheel pivot to the pilot's grip.
- Rudder pedal force - Difference of push-force components of forces exerted by the pilot on the rudder pedals, lying in planes parallel to the plane of symmetry, measured perpendicular to the pedals at the normal point of application of the pilot's instep on the respective rudder pedals

- Control surface - A device such as an external surface which is positioned by a cockpit control or stability augmentation to produce aerodynamic or jet-reaction type forces for controlling the attitude of the vehicle. As used in this specification the elevator surface, aileron surface, and rudder surface are the control surfaces or devices which are controlled by the stick or wheel and rudder pedals, and automatically by stability augmentation systems.
- Direct normal force control - A device producing direct normal force for the primary purpose of controlling the flight path of the vehicle. Direct normal force control is the descriptive title given to the concept of directly modulating the normal force on a vehicle by changing its lifting capabilities at a constant angle of attack and constant airspeed or by controlling the normal force component of such items as jet exhausts.
- Control power - Effectiveness of control surfaces in applying forces or moments to a vehicle. For example, 50% of available aileron control power is 50% of the maximum rolling moment that is available to the pilot with allowable aileron control force.

6.2.5 Longitudinal parameters

- ζ_{sp} - damping ratio of the short-period oscillation
- $\omega_{n_{sp}}$ - undamped natural frequency of the short-period oscillation
- ζ_p - damping ratio of the phugoid oscillation
- ω_{n_p} - undamped natural frequency of the phugoid oscillation
- n - normal acceleration or normal load factor, measured at the c.g.
- n_L - symmetrical flight limit load factor for a given Vehicle Normal State, based on structural considerations
- n_{max}, n_{min} - maximum and minimum Service load factors

- $n(+), n(-)$ - for a given altitude, the upper and lower boundaries of n in the V-n diagrams depicting the Service Flight Envelope
- n_{Omax}, n_{Omin} - maximum and minimum operational load factors
- $n_O(+), n_O(-)$ - for a given altitude, the upper and lower boundaries of n in the V-n diagrams depicting the Operational Flight Envelope



- α - angle of attack; the angle in the plane of symmetry between the fuselage reference line and the tangent to the flight path at the vehicle center of gravity
- α_s - the stall angle of attack at constant speed for the configuration, weight, center-of-gravity position and external-store combination associated with a given Vehicle Normal State; defined as the lowest of the following:
- Angle of attack for the highest steady load factor, normal to the flight path, that can be attained at a given speed or Mach number

- b. Angle of attack, for a given speed or Mach number, at which abrupt uncontrollable pitching, rolling or yawing occurs, i.e., loss of control about a single axis
- c. Angle of attack, for a given speed or Mach number, at which intolerable buffeting is encountered
- d. An arbitrary angle of attack allowed by 3.1.9.2.1

n/α	- the steady-state normal acceleration change per unit change in angle of attack for an incremental elevator deflection at constant speed (airspeed and Mach number)
F_S/n	- gradient of steady-state elevator control force versus n at a constant speed (3.2.2.2.1)
γ	- flight path angle, $\gamma = \sin^{-1} \frac{\text{vertical speed}}{\text{true airspeed}}$, positive for climbing flight
L	- aerodynamic lift plus thrust component, normal to the flight path
Flare time	- For an unpowered vehicle during landing, the time from the initiation of flare to the completion of flare. Flare is initiated by pulling g's from an equilibrium glide. Flare is completed when the flight path angle is near zero ($\gamma \approx 0$) at an altitude no greater than 50 feet above ground level.
Float time	- For an unpowered vehicle, the time from the completion of the landing flare to touchdown.

6.2.6 Lateral-directional parameters

δ_{AS}	- displacement of the aileron control stick or wheel along its path
τ_R	- first-order roll mode time constant, positive for stable mode
τ_S	- first-order spiral mode time constant, positive for stable mode

- ω_{η_d} - undamped natural frequency of the Dutch roll oscillation
- ζ_d - damping ratio of the Dutch roll oscillation
- ϕ - bank angle measured in the y-z plane, between the y axis and the horizontal (6.2.1)
- ϕ_t - bank angle change in time t, in response to control deflection of the form given in 3.3.4
- ρ - roll rate about the x-axis (6.2.1)
- $\frac{\rho_{osc}}{\rho_{AV}}$ - a measure of the ratio of the oscillatory component of roll rate to the average component of roll rate following a rudder-pedals-free step aileron control command:

$$\zeta_d \leq 0.2; \quad \frac{\rho_{osc}}{\rho_{AV}} = \frac{\rho_1 + \rho_3 - 2\rho_2}{\rho_1 + \rho_3 + 2\rho_2}$$

$$\zeta_d > 0.2; \quad \frac{\rho_{osc}}{\rho_{AV}} = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$$

where ρ_1 , ρ_2 , and ρ_3 are roll rates at the first, second and third peaks, respectively (see figures 9 and 10)

- $\frac{\phi_{osc}}{\phi_{AV}}$ - a measure of the ratio of the oscillatory component of a bank angle to the average component of bank angle following a rudder-pedals-free impulse aileron control command:

$$\zeta_d \leq 0.2; \quad \frac{\phi_{osc}}{\phi_{AV}} = \frac{\phi_1 + \phi_3 - 2\phi_2}{\phi_1 + \phi_3 + 2\phi_2}$$

$$\zeta_d > 0.2; \quad \frac{\phi_{osc}}{\phi_{AV}} = \frac{\phi_1 - \phi_2}{\phi_1 + \phi_2}$$

where ϕ_1 , ϕ_2 and ϕ_3 are bank angles at the first, second and third peaks, respectively

- β - sideslip angle at the center of gravity, angle between undisturbed flow and plane of symmetry. Positive, or right, sideslip corresponds to incident flow approaching from the right side of the plane of symmetry.

$\Delta\beta_{max}$

- maximum sideslip excursion at the c.g., occurring within two seconds or one half-period of the Dutch roll, whichever is greater, for a step aileron-control command

t

- ratio of "commanded roll performance" to "applicable roll performance requirement" of 3.3.4 or 3.3.4.1, where:

- "Applicable roll performance requirement", (ϕ_t) requirement, is determined from 3.3.4 and 3.3.4.1 for the Class, Flight Phase Category and Level under consideration
- "Commanded roll performance", (ϕ_t) command, is the bank angle attained in the stated time for a given step aileron command with rudder pedals employed as specified in 3.3.4 and 3.3.4.1

$$X = \frac{(\phi_t)_{\text{command}}}{(\phi_t)_{\text{requirement}}}$$

$t_{n\beta}$

- time for the Dutch roll oscillation in the sideslip response to reach the n th local maximum for a right step or pulse aileron-control command, or the n th local minimum for a left command. In the event a step control input cannot be accomplished, the control shall be moved as abruptly as practical and, for purposes of this definition, time shall be measured from the instant the cockpit control deflection passes through half the amplitude of the commanded value. For pulse inputs, time shall be measured from a point halfway through the duration of the pulse.

ψ_β

- phase angle in a cosine representation of the Dutch roll component of sideslip - negative for a lag

$$\psi_\beta = -\frac{360}{T_d} t_{n\beta} + (n-1) 360 \text{ (degrees)}$$

with n as in $t_{n\beta}$ above

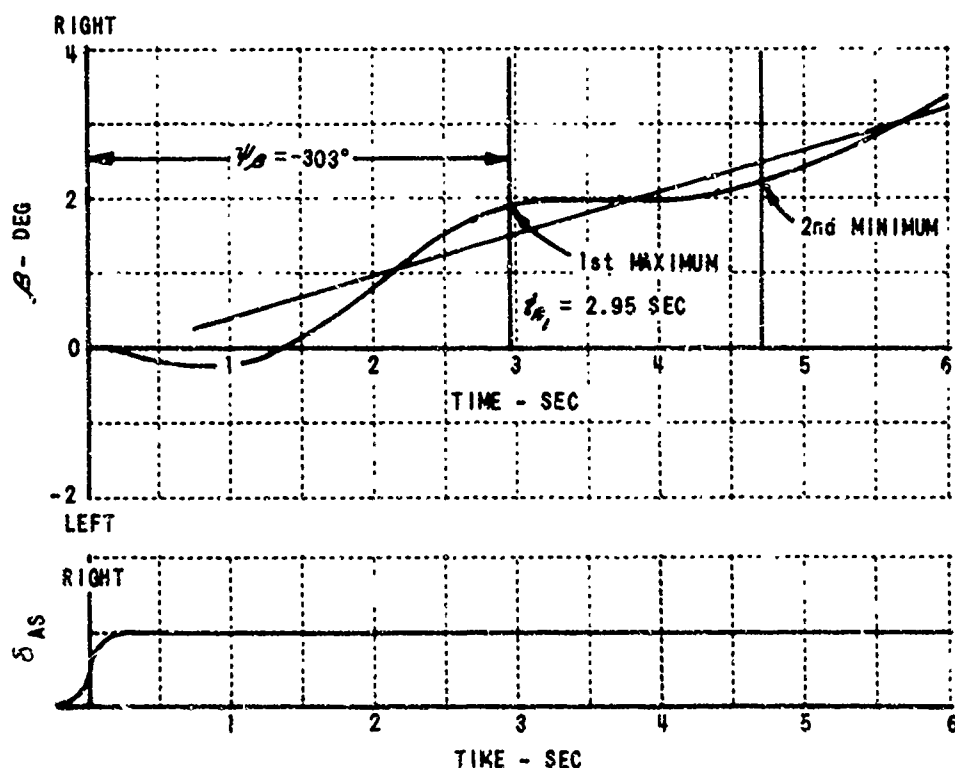
$$\psi \frac{p}{\beta}$$

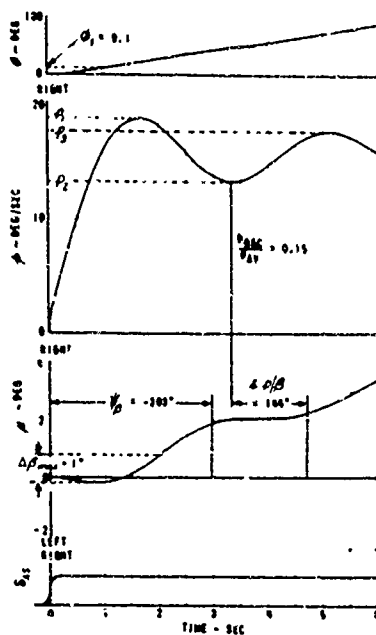
- phase angle between roll rate and sideslip in the free Dutch roll oscillation. Angle is positive when p leads β

$$\left| \frac{\phi}{\beta} \right|_d$$

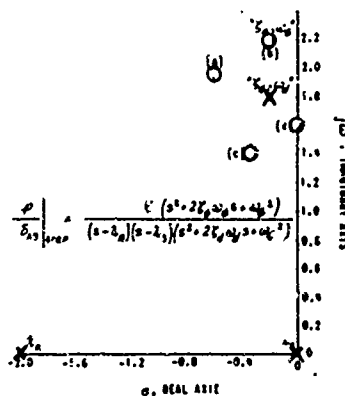
- at any instant, the ratio of amplitudes of the bank-angle and sideslip-angle envelope in the Dutch roll mode

Examples showing measurement of roll-sideslip coupling parameters are given in figure 9 for right rolls and figure 10 for left rolls. Since several oscillations for the Dutch roll are required to measure these parameters, and since for proper identification large roll rates and bank angle changes must generally be avoided, for flight test, step aileron inputs should generally be small. It should be noted that since ψ_β is the phase angle of the Dutch roll component of sideslip, care must be taken to select a peak far enough downstream that the position of the peak is not influenced by the roll mode. In practice, peaks occurring one or two roll mode time constants after the aileron input will be relatively undistorted. Care must also be taken when there is ramping of the sideslip trace, since ramping will displace the position of a peak of the trace from the corresponding peak of the Dutch roll component. In practice, the peaks of the Dutch roll component of sideslip are located by first drawing a line through the ramping portion of the sideslip trace and then noting the times at which the vertical distance between the line and the sideslip trace is the greatest. (See following sketch for Case (a) of figures 9 and 10.)

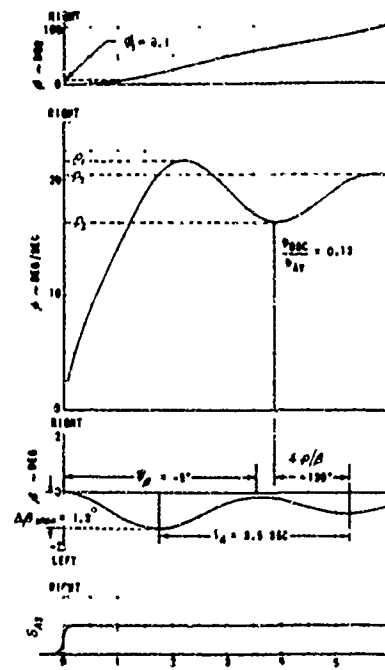




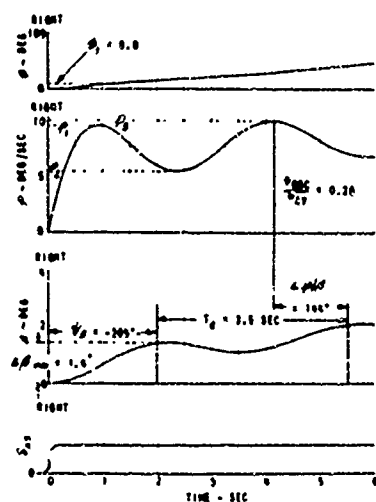
(a)



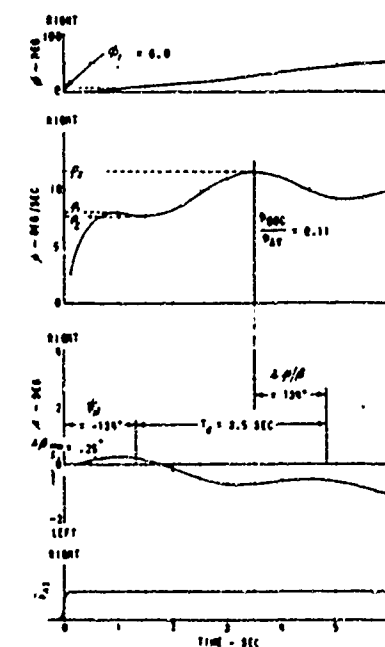
TRANSFER FUNCTION
 $\frac{\phi}{\delta_{AS}} \bigg|_{STEP}$



(b)

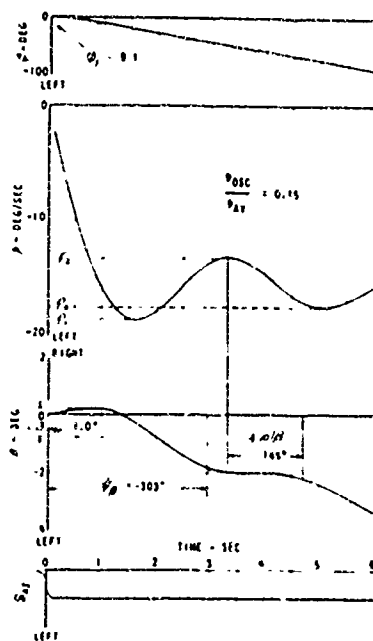


(c)

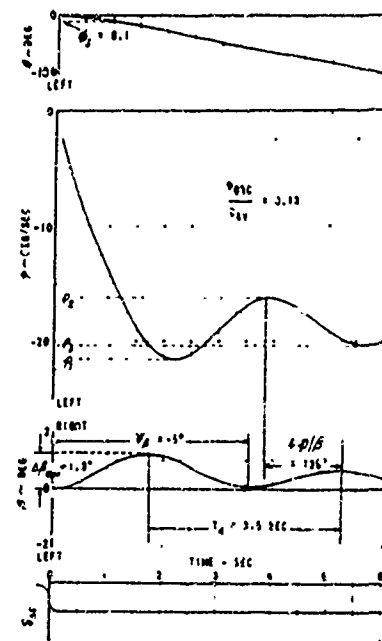


(d)

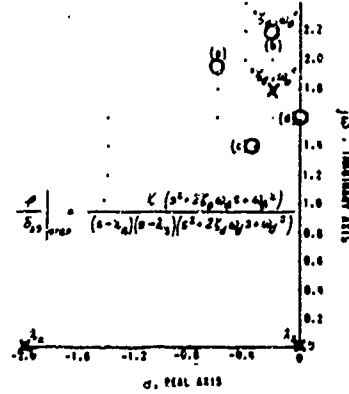
Figure 9 ROLL - SIDESLIP COUPLING PARAMETERS
 RIGHT ROLLS



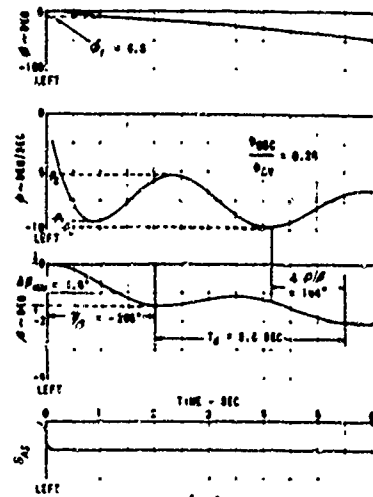
(a)



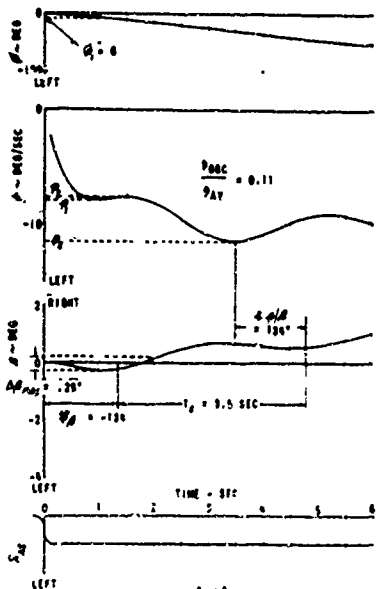
(b)



$\frac{p}{\delta_{AS}} \bigg|_{STEP}$ TRANSFER FUNCTION



(c)



(d)

Figure 10 ROLL - SIDESLIP COUPLING PARAMETERS
LEFT ROLLS

Since the first local maximum of the Dutch roll component of the sideslip response occurs at $t = 2.95$ seconds,

$$\psi_{\beta} = \frac{-360}{T_d} t_{n_{\beta}} + (n-1)360 = \frac{-360}{3.5} (2.95) = -303^{\circ}$$

Let us assume that the roll performance requirement, upon which the parameter " ϵ " in the sideslip excursion requirement (figure 6) is based, is $\phi_{\epsilon} = 30$ degrees in 1 second with rudder pedals free (as in the rolls of 3.3.2.4). From the definitions, " ϵ " for this condition is:

$$\epsilon = \frac{(\phi_{\epsilon})_{\text{command}}}{(\phi_{\epsilon})_{\text{requirement}}}$$

Therefore, from figures 9 and 10 for:

Case (a), $\epsilon = \frac{9.1}{30} = 0.30$

Case (c), $\epsilon = \frac{6.8}{30} = 0.23$

Case (b), $\epsilon = \frac{8.1}{30} = 0.27$

Case (d), $\epsilon = \frac{6.0}{30} = 0.20$

6.2.7 Atmospheric disturbances parameters

- Ω - spatial (reduced) frequency (radians per foot)
- ω - temporal frequency (radians per second),
where $\omega = \Omega V$
- u_g - random gust velocity along the x body axis
(feet per second)
- v_g - random gust velocity along the y body axis
(feet per second)
- w_g - random gust velocity along the z body axis
(feet per second)

Note: u_g , v_g , w_g have Gaussian (normal) distributions, and are defined positively along the positive vehicle body axes.

- σ - root-mean-square gust intensity, where

$$\sigma^2 = \int_0^{\infty} \Phi(\Omega) d\Omega = \int_0^{\infty} \phi(\omega) d\omega$$

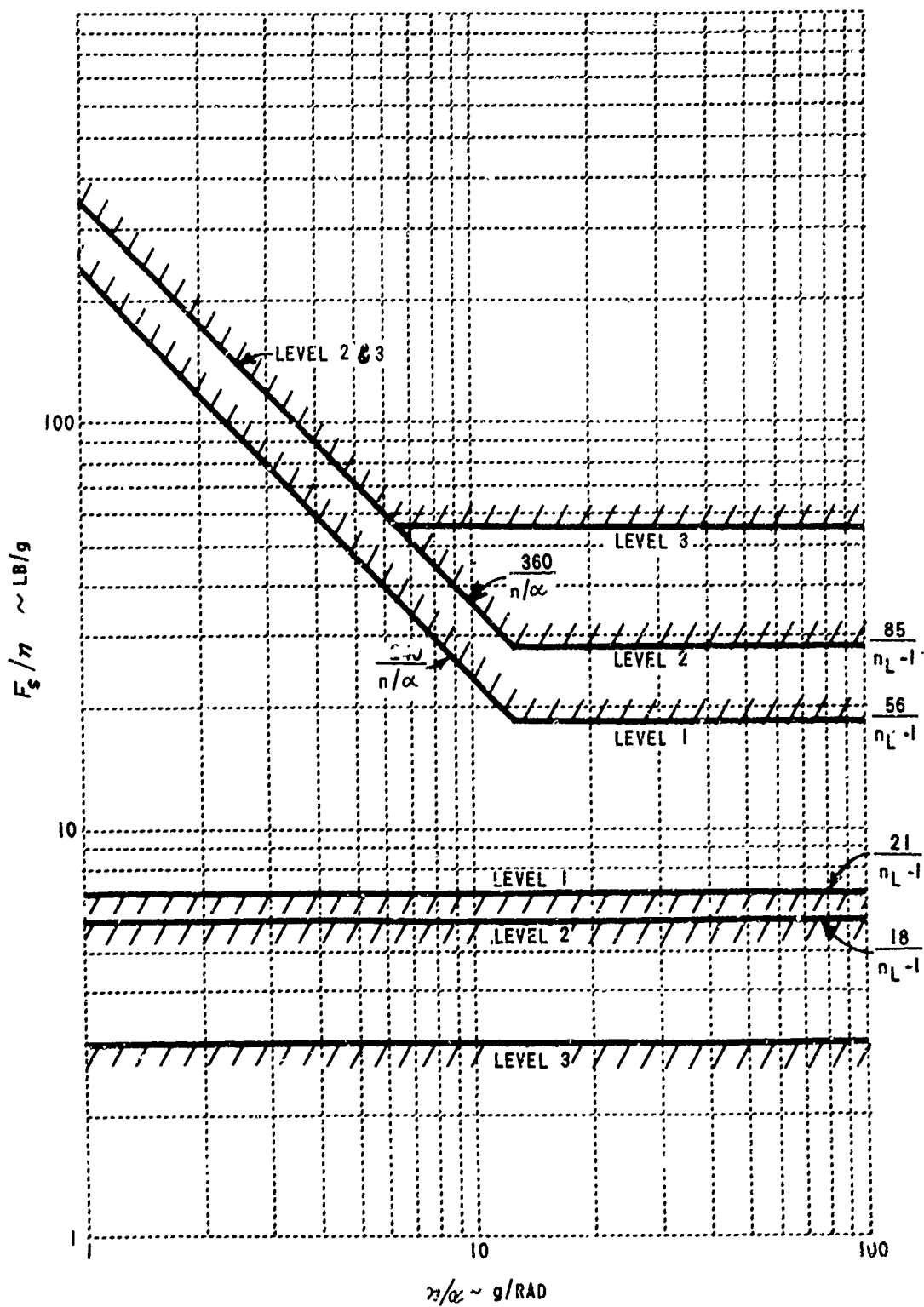


FIGURE 11 ELEVATOR MANEUVERING FORCE GRADIENT LIMITS:
CENTER-STICK CONTROLLER, $n_L = 4.0$

σ_u	- root-mean-square intensity of u_g
σ_v	- root-mean-square intensity of v_g
σ_w	- root-mean-square intensity of w_g
L_u	- scale for u_g (feet)
L_v	- scale for v_g (feet)
L_w	- scale for w_g (feet)
$\Phi_{u_g}(\Omega)$	- spectrum for u_g , where $\Phi_{u_g}(\Omega) = V\phi_{u_g}(\omega)$
$\Phi_{v_g}(\Omega)$	- spectrum for v_g , where $\Phi_{v_g}(\Omega) = V\phi_{v_g}(\omega)$
$\Phi_{w_g}(\Omega)$	- spectrum for w_g , where $\Phi_{w_g}(\Omega) = V\phi_{w_g}(\omega)$
v_m	- generalized discrete gust velocity, positive along the positive vehicle body axes, $m = x, y, z$ (feet per second)
d_m	- generalized discrete gust length (always positive) $m = x, y, z$ (feet)

6.3 Interpretation of the F_S/n limits of table V. Because the limits on F_S/n are a function of both n_L and n/α , table V is rather complex. To illustrate its use, the limits are presented on figure 11 for a vehicle having a center-stick controller and $n_L = 4.0$.

6.4 Gain scheduling. Changes of mechanical gearings and stability augmentation gains in the primary flight control system are sometimes accomplished by scheduling the changes as a function of the settings of secondary control devices, such as flaps or wing sweep. This practice is generally acceptable, but gearings and gains normally should not be scheduled as a function of trim control settings since pilots do not always keep vehicles in trim.

6.5 Engine considerations. Secondary effects of engine operation may have an important bearing on flying qualities and should not be overlooked in design. These considerations include such effects as engine gyroscopic moments influencing airframe dynamic motions, the effects of engine operation on spin characteristics and spin recovery, and the variation of engine-derived power for actuating the flight controls with engine speed.

6.6 Effects of aeroelasticity, control equipment, and structural dynamics. Since aeroelasticity, control equipment, and structural dynamics may exert an important influence on the vehicle flying qualities, such effects should not be overlooked in calculations or analyses directed toward investigation of compliance with the requirements of this specification.

6.7 Application of Levels. Part of the intent of 3.1.10 is to ensure that the probability of encountering significantly degraded flying qualities because of component or subsystem failures is small. For example, the probability of encountering very degraded flying qualities (Level 3) must be less than specified values per flight.

6.7.1 Theoretical compliance. To determine theoretical compliance with the requirements of 3.1.10.2, the following steps must be performed:

- a. Identify those Vehicle Failure States which have a significant effect on flying qualities (3.1.6.2)
- b. Define the longest flight duration to be encountered during operational missions (3.1.1)
- c. Determine the probability of encountering various Vehicle Failure States, per flight, based on the above flight duration (3.1.10.2)
- d. Determine the degree of flying qualities degradation associated with each Vehicle Failure State in terms of Levels as defined in the specific requirements.
- e. Determine the most critical Vehicle Failure States (assuming the failures are present at whichever point in the Flight Envelope being considered is most critical in a flying qualities sense), and compute the total probability of encountering Level 2 flying qualities in the Operational Flight Envelope due to equipment failures. Likewise, compute the probability of encountering Level 3 flying qualities in the Operational Flight Envelope, etc.
- f. Compare the computed values above with the requirements in 3.1.10.2 and 3.1.10.3. An example which illustrates an approximate estimate of the probabilities of encounter follows: if the failures are all statistically independent, determine the sum of the probabilities of encountering all Vehicle Failure States which degrade flying qualities to Level 2 in the Operational Envelope. This sum must be less than 10^{-2} per flight.

If the requirements are not met, the designer must consider alternate courses such as:

- a. Improve the vehicle flying qualities associated with the more probable Failure States, or
- b. Reduce the probability of encountering the more probable Failure States through equipment redesign, redundancy, etc.

Regardless of the probability of encountering any given Vehicle Failure States (with the exception of Special Failure States), the flying qualities shall not degrade below Level 3.

6.7.2 Level definitions. To determine the degradation in flying qualities parameters for a given Vehicle Failure State, the following definitions are provided:

- a. Level 1 is better than or equal to the Level 1 boundary, or number, given in Section 3.
- b. Level 2 is worse than Level 1, but no worse than the Level 2 boundary, or number.
- c. Level 3 is worse than Level 2, but no worse than the Level 3 boundary, or number.

When a given boundary, or number, is identified as Level 1 and Level 2, this means that flying qualities outside the boundary conditions shown, or worse than the number given, are at best Level 3 flying qualities. Also, since Level 1 and Level 2 requirements are the same, flying qualities must be within this common boundary, or number, in both the Operational and Service Flight Envelopes for Vehicle Normal States (3.1.10.1). Vehicle Failure States that do not degrade flying qualities beyond this common boundary are not considered in meeting the requirements of 3.1.10.2. Vehicle Failure States that represent degradations to Level 3 must, however, be included in the computation of the probability of encountering Level 3 degradations in both the Operational and Service Flight Envelopes. Again degradation beyond the Level 3 boundary is not permitted regardless of component failures.

6.7.3 Computational assumptions. Assumptions a and b of 3.1.10.2 are somewhat conservative, but they simplify the required computations in 3.1.10.2 and provide a set of workable ground rules for theoretical predictions. The reasons for these assumptions are:

- a. "...components and systems are...operating for a time period per flight equal to the longest operational mission time...". Since most component failure data are in terms of failures per flight hour, even though continuous operation may not be typical (e.g., yaw damper on during supersonic flight only), failure probabilities must be predicted on a per flight basis using a "typical" total flight time. The "longest operational mission time" as "typical" is a natural result. If acceptance cycles-to-failure reliability data are available (MIL-STD-756), these data may be used for prediction purposes based on maximum cycles per operational mission, subject to procuring activity approval. In any event, compliance with the requirements of 3.1.10.2 as determined in accordance with section 4, is based on the probability of encounter per flight.
- b. "...failure is assumed to be present at whichever point...is most critical...". This assumption is in keeping with the requirements of 3.1.6.2 regarding Flight Phases subsequent to the actual failure in question. In cases that are unrealistic from the operational standpoint, the specific Vehicle Failure States might fall in the Vehicle Special Failure State classification (3.1.6.2.1).

6.8 Related documents. The documents listed below, while they do not form a part of this specification, are so closely related to it that their contents should be taken in account in any application of this specification.

SPECIFICATIONS

Military

MIL-C-5011	Charts; Standard Aircraft Characteristics and Performance, Piloted Aircraft
MIL-S-5711	Structural Criteria, Piloted Airplanes, Structural Tests, --- Flight
MIL-M-7700	Manual, Flight
MIL-A-8860	Airplane Strength and Rigidity - General Specification for
MIL-A-8861	Airplane Strength and Rigidity - Flight Loads
MIL-G-38478	General Requirements for Angle of Attack Based Systems

Section III

FLYING QUALITIES RATIONALE, BACKUP DATA AND USER'S GUIDE

Before presenting the rationale and backup data to support the handling qualities requirements of Section II, it may be well to discuss briefly past history and the present status of a lifting re-entry vehicle handling qualities specification. It will then be possible to view the requirements presented in Section II and the rationale and backup data in this section with a proper perspective.

The development of handling qualities requirements for lifting re-entry vehicles has been a problem of interest to the Flight Dynamics Laboratory at Wright Field over a number of years. The first vehicle to which such requirements were applied as an aid in design and development was the X-20 (Dyna-Soar) re-entry vehicle.

A preliminary investigation of handling qualities requirements for lifting re-entry vehicles was completed in May, 1969 (Reference 1). This study was completed for the Air Force Flight Dynamics Laboratory under Contract AF33(615)-3294 and is based on the Air Force's continuing interest in the military potential of lifting re-entry vehicles. This investigation surveyed the literature and some of the important problems associated with specification of handling qualities requirements for lifting re-entry vehicles throughout the flight envelope of such vehicles. Suggestions were made on how these problems might be attacked through analysis and simulation so that handling qualities requirements could be developed.

Based on the preliminary investigation of Reference 1, the Flight Research Department of CAL, under contract to the Air Force Flight Dynamics Laboratory (Contract F33615-69-C-1906), prepared a working draft of preliminary handling requirements for lifting re-entry vehicles completed in July, 1970 (Reference 9). These requirements were to be applied to small lifting re-entry vehicles of medium to high maneuverability based on hypersonic $(L/D)_{max}$. Requirements were confined to the terminal phase of re-entry flight at low supersonic, transonic, and subsonic speeds. This preliminary draft was developed in support of the design and analysis of the FDL-8 from the standpoint of handling qualities. The FDL-8 is a high-hypersonic $(L/D)_{max}$ lifting re-entry vehicle developed primarily "in-house" at the Flight Dynamics Laboratory. As part of this contract the Flight Research Department of CAL also gave some handling qualities support to both the FDL-8 and FDL-7 lifting body projects at the Flight Dynamics Laboratory. An additional part of this investigation was a preliminary analysis of some of the unique aspects of lifting re-entry dynamics (Reference 6).

The lifting re-entry vehicle handling qualities requirements, rationale, and substantiating data presented in this report are a follow-on of the work performed in the two previous years. This work has been performed for the Air Force Flight Dynamics Laboratory under Contract No. F33615-70-C-1755.

Copies of the working draft developed in the previous year (Reference 10) were sent to the contractors and government agencies listed in the Foreword. During the month of January 1971, review meetings were held with these contractors and government agencies. The requirements presented in this report reflect those comments that seemed pertinent to the development of general lifting re-entry vehicle handling qualities requirements during terminal flight at low supersonic, transonic, and subsonic flight. The requirements are also based on the lifting re-entry vehicle handling qualities literature and they are an expansion and revision of the requirements in Reference 9. The present requirements cover both large and small vehicles and vehicles with both low and high cross-range based on hypersonic $(L/D)_{max}$ and load factor. The rationale and backup data presented in this section are also a revision and expansion of Reference 9.

In the past year, several other investigations of handling qualities specification requirements for a specific vehicle, the Space Shuttle, have been undertaken. The NASA Flight Research Center at Edwards Air Force Base has proposed a flying qualities specification for Space Shuttle vehicles. In its present form, the specification is intended as a working draft and it is based primarily, but not exclusively, on MIL-F-8785B(ASG). A preliminary stability and control specification for the Space Shuttle Booster, not a handling qualities specification as such, has been proposed by General Dynamics, Convair Division. This specification has been used in some of their design efforts on the Space Shuttle Booster. Handling qualities criteria for the Space Shuttle Orbiter are presently under investigation by Systems Technology Inc. (STI) under contract to NASA Ames. All of these efforts, to the extent that they are presently understood, have influenced to some extent the requirements and rationale as they are presented in this report. This section is written in support of the handling qualities requirements presented in Section II. It supports the Section II requirements by presenting the rationale and backup data upon which the requirements are based. The rationale, backup data, and the discussion of specific requirements are also useful as a user's guide. They explain what the specific requirements are attempting to provide, and how well founded these requirements are in the sense that they are or are not supported by actual data. It becomes readily apparent where additional handling qualities research effort is required, and this is discussed in terms of handling qualities research programs in Reference 10.

An examination of the requirements in Section II makes it readily apparent that many of the requirements for lifting re-entry vehicles are the same or adaptations of the requirements for piloted airplanes as they appear in Reference 2. Lifting re-entry vehicles, when cruising, gliding or maneuvering near the terminal phase of re-entry at low supersonic, transonic, and subsonic speeds are subjected to the same flight environment and require piloting tasks similar to those of conventional airplanes. In fact, some of the data used in establishing some of the requirements in Reference 2 were obtained from fixed-base and in-flight handling qualities simulation programs on lifting re-entry vehicles.

In adapting requirements in Reference 2 to lifting re-entry vehicles, care has been taken to account for the differences as well as the similarities between conventional airplanes and lifting re-entry vehicles during terminal flight. An examination of these differences and similarities has extended to vehicle Classes, Flight Phases, handling qualities Levels, and individual handling qualities requirements. Some requirements have been added that are new and possibly unique to lifting re-entry vehicles.

In the discussion of individual requirements, extensive comments are made only on those requirements that have been altered considerably from similar requirements in MIL-F-8785B(ASG) (Reference 7), or on specific requirements that are completely unique to lifting re-entry vehicles. When the data to support particular requirements is essentially that contained in Reference 8, the data is not repeated here. One should refer to Reference 8 for the rationale and substantiating data.

The actual statement of the requirements that appear in Section II is not repeated in this section, only the paragraph numbers and titles are repeated as they appear in Section II. In some cases, several paragraphs and requirements are discussed together since they are interrelated and the discussion applies equally well to all the paragraphs and requirements.

Requirements

1. Scope and classifications
- 1.1 Scope
- 1.2 Application
- 1.3 Classification of vehicles
- 1.3.1 Operational or experimental designation

Discussion

The working draft of lifting re-entry vehicle handling qualities requirements (Reference 9) was limited both in scope and in the proposed classification scheme. It was stated that the scope of the specification was limited to medium-to-high maneuverability lifting re-entry vehicles during flight at low supersonic, transonic and subsonic speeds in the lower atmosphere. The specification was restricted to small lifting re-entry vehicles with an $(L/D)_{\max}$ at hypersonic speeds greater than 1.5, but possibly as low as 1.0. Therefore, the specification was considered to be applicable to lifting bodies that have flown such as the M2-F2, HL-10, and X-24. It was also considered to be applicable to vehicles that have been designed and wind tunnel tested, but not built or flown, such as the X-20 (Dyna-Soar), FDL-7, FDL-8, etc. In Reference 9, re-entry vehicles were further categorized as to Class, based on whether the vehicle mission is to be considered operational or experimental. In some cases, for a vehicle designed specifically

for experimental use, the requirements were relaxed for the same level of flying qualities. This seemed rational based on the more restricted missions, limited flight envelopes, ideal flight environment, and the intensive training and high skill of pilots that would be used for experimental missions.

In essence, the requirements in Reference 9 were limited to two Classes of re-entry vehicles, small operational and small experimental vehicles, during flight at the terminal phase of re-entry at low supersonic, transonic, and subsonic speeds. Such requirements obviously do not cover the entire scope of lifting re-entry vehicle Classes as they are presently envisioned. Since the classification of lifting re-entry vehicles based on vehicle missions is central to the specification of flying qualities, it is important to set up a classification scheme before detailed requirements can be formulated.

It is suggested in Reference 1 that a classification of lifting re-entry vehicles based on hypersonic $(L/D)_{\max}$ may be most descriptive of the vehicles in terms of their missions and therefore their handling qualities requirements. A suggested classification based on $(L/D)_{\max}$ at hypersonic speeds taken from Reference 1 is the following:

Classification Based on Hypersonic $(L/D)_{\max}$

<u>Class</u>	<u>Description</u>
I	Low $(L/D)_{\max}$: $0.5 < (L/D)_{\max} < 1.5$
II	Medium $(L/D)_{\max}$: $1.5 < (L/D)_{\max} < 2.5$
III	High $(L/D)_{\max}$: $(L/D)_{\max} > 2.5$

It is suggested in Reference 1 that a further subclassification that would aid in defining the lifting re-entry mission, flight phases, and tasks, and relating these to flying qualities requirements might be the following:

Subclassification a - based on hypersonic flight speed within and out of the sensible atmosphere

<u>Subclass a</u>	<u>Description</u>
a(1)	Superorbital
a(2)	Orbital
a(3)	Suborbital

Subclassification b - based on the configuration for terminal glide and landing

<u>Subclass b</u>	<u>Description</u>
b(1)	Fixed Geometry
b(2)	Variable Geometry
b(3)	Decoupled Landing

Including all classes and subclasses, the classification scheme of Reference 1 allows for 27 different classes of vehicles that may or may not have distinct flying qualities requirements during the different flight phases at hypersonic, supersonic, and subsonic flight. It is noteworthy that flight vehicles exist for just one of these 27 classes, and designs and analytical studies for re-entry vehicles presently proposed, or proposed in the past, fit only a few of these categories. Flight vehicles such as Mercury, Gemini, and Apollo fall below an $(L/D)_{\max}$ of 0.5 and therefore are excluded as lifting re-entry vehicles based on this classification. Flight vehicles such as the M2-F2, HL-10, and the X-24A would be included as Class I - a(3) - b(1). All the proposed lifting re-entry vehicles having an $(L/D)_{\max}$ at hypersonic speeds greater than 0.5, upon which information appears in the literature, whether or not a flight vehicle has been designed, are categorized according to this classification matrix as shown in Table XV.

Size or weight, as it may be related to load factor and maneuverability, and hence the mission of the vehicle, is not a factor in the classification scheme of Reference 1. Only cross-range as related to $(L/D)_{\max}$ at hypersonic speeds is a consideration. The classification scheme of Reference 1 requires modification since the Space Shuttle Booster, which is comparable in size to a Boeing 747 or Lockheed C-5A, is grouped with the smaller and more highly maneuverable M2-F2, HL-10, and X-24A vehicles.

In Reference 8, the Background Information and User Guide for MIL-F-8785B(ASG), a statement is made that flying qualities requirements for conventional airplanes are tailored according to:

- (1) the kind of airplane (Class)
- (2) the job to be done (Flight Phase), and
- (3) how well the job must be done (Level).

The airplane mission is defined in a broad sense by the airplane Class, and MIL-F-8785B(ASG) categorizes airplanes into four Classes. Each Class is somewhat related to weight and maneuverability, and through these to the load factor for which the airplane is designed. None of these Classes is mutually exclusive. Overlapping in terms of weight, maneuverability, and load factor exists between types of airplanes categorized in the different Classes based on missions, especially missions as they may be related to

TABLE XV
CLASSIFICATION OF LIFTING RE-ENTRY VEHICLES
(BASED ON REFERENCE 1)

CLASS	SUBCLASS a	SUBCLASS b		
		FIXED GEOMETRY	VARIABLE GEOMETRY	DECOUPLED GEOMETRY
I LOW $(L/D)_{\max}$ $0.5 < (L/D)_{\max} < 1.5$	a(1) SUPERORBITAL			
	a(2) ORBITAL	X-20, SPACE SHUTTLE (ORBITER)	SPACE SHUTTLE (ORBITER)	SPACE SHUTTLE (ORBITER)
	a(3) SUBORBITAL	M2-F2, HL-10 X-24, SPACE SHUTTLE (BOOSTER)	SPACE SHUTTLE (BOOSTER)	SPACE SHUTTLE (BOOSTER)
II MEDIUM $(L/D)_{\max}$ $1.5 < (L/D)_{\max} < 2.5$	a(1) SUPERORBITAL			
	a(2) ORBITAL	SPACE SHUTTLE (ORBITER)	SPACE SHUTTLE (ORBITER)	
	a(3) SUBORBITAL			
III HIGH $(L/D)_{\max}$ $(L/D)_{\max} > 2.5$	a(1) SUPERORBITAL			
	a(2) ORBITAL	FDL-7, FDL-8, SPACE SHUTTLE (ORBITER)	FDL-7, FDL-8, SPACE SHUTTLE (ORBITER)	
	a(3) SUBORBITAL	FDL-8 (EXPERIMENTAL)		

handling qualities. A great deal of operational experience with conventional airplanes over many years makes the classification of airplanes in MIL-F-8785B(ASG) both reasonable and rational. Unfortunately, such experience does not exist for lifting re-entry vehicles. In order to compare airplane Classes to suggested lifting re-entry vehicle Classes, it may be well to restate the airplane classification of MIL-F-8785B(ASG):

- Class I - Small, light airplanes
- Class II - Medium weight, low-to-medium maneuverability airplanes
- Class III - Large, heavy, low-to-medium maneuverability airplanes
- Class IV - High maneuverability airplanes.

In attempting to classify lifting re-entry vehicles, it is well to keep in mind the rationale used in classifying military airplanes. This classification is based primarily on weight and maneuverability, and the airplane maneuverability is based to a large extent on the airplane design load factor. In general, the larger the airplane, the lower the design load factor and the lower the maneuverability. The lower design load factor and maneuverability as the weight increases are considered acceptable since the missions, for which larger and heavier airplanes are designed, can be fulfilled with lower maneuverability. This correspondence between size and weight, maneuverability, and load factor is not always satisfied since the airplane mission and maneuverability are not always primarily related to airplane weight. Such is the case for Class I airplanes (small, light airplanes) which are not designed to as high load factors as small fighters. The circumstances are the same for some medium weight airplanes which may be in Class II or Class IV depending on their mission. For example, the FB-111 is classified as a bomber and placed in Class II, but the weight is not that significantly different from the F-111A, the fighter version, that is placed in Class IV.

In consideration of the previous discussion, it is possible to suggest several ways of classifying a lifting re-entry vehicle based on the vehicle mission as it can be related to vehicle size, maneuverability, mode of operation, and tasks during its important flight phases. These possible classifications are suggested below.

1. Classification Based on Mission as it Relates to Weight and Maneuverability

<u>Class</u>	<u>Description</u>
III	medium-to-heavy weight, low-to-medium maneuverability
IV	light-to-medium weight, medium-to-high maneuverability.

2. Classification Based on Mission as it Relates to Cross-Range as Determined by Hypersonic $(L/D)_{\max}$

<u>Class</u>	<u>Description</u>
H(1)	$(L/D)_{\max} < 0.5$
H(2)	$0.5 < (L/D)_{\max} < 1.5$
H(3)	$(L/D)_{\max} > 1.5$

3. Classification Based on Intended Use of Lifting Re-Entry Vehicles

<u>Class</u>	<u>Description</u>
O	Operational Vehicle
E	Experimental Vehicle

If all of these classes are considered to be sufficiently distinct and not interrelated, this type of classification will allow for 36 classes of lifting re-entry vehicles. For many of these classes, no vehicles presently exist or are even envisioned. A possible classification of lifting re-entry vehicles, built, designed, or presently hypothesized, based on this classification scheme, is shown in Table XVI.

The only convenient way of designating some of the proposed Space Shuttle Vehicle configurations in Table XVI is by numbers, 1 through 12. The letters in parentheses following the numbers are used to designate whether the vehicle is the Space Shuttle Vehicle Orbiter or Booster as indicated by the key below Table XVI. Re-entry vehicles 1 through 12 have appeared recently in References 11 through 19. A short description of these vehicles is helpful in examining Table XVI and is presented below:

1. Bell's ACLS (Reference 11)

Bell's Air Cushion Landing System (ACLS) would be used in landing a Space Shuttle Orbiter (SSO) of up to 200,000 pounds and a Space Shuttle Booster (SSB) of up to 700,000 pounds.

2. Chrysler's Single Stage-to-Orbit Vehicle (Reference 12)

Chrysler's Single Stage-to-Orbit Space Shuttle System would use V/STOL techniques for the terminal landing mode.

TABLE XVI
SUGGESTED CLASSIFICATION OF LIFTING RE-ENTRY VEHICLES

CLASSIFICATION BASED ON TERMINAL GLIDE AND LANDING MODE	INTENDED USE	CLASSIFICATION BASED ON WEIGHT, MANEUVERABILITY, AND CROSS-RANGE					
		III			IV		
		MEDIUM-TO-HEAVY WEIGHT, LOW-TO-MEDIUM MANEUVERABILITY			SMALL-TO-MEDIUM WEIGHT, MEDIUM-TO-HIGH MANEUVERABILITY		
		HYPERSONIC (L/D) _{max}			HYPERSONIC (L/D) _{max}		
		H(1)	H(2)	H(3)	H(1)	H(2)	H(3)
		(L/D) _{max} < 0.5	0.5 < (L/D) _{max} < 1.5	(L/D) _{max} > 1.5	(L/D) _{max} < 0.5	0.5 < (L/D) _{max} < 1.5	(L/D) _{max} > 1.5
L(1) (L/D) _{max} < 2.5 (DECOUPLED LANDING MODE)	O		1(O) & (B); 2(O); 3(O);		MERCURY; GEMINI; APOLLO;		
L(2)	E				GEMINI PARAGLIDER		
2.5 < (L/D) _{max} < 5.0	O		5(B); 6(O ₂) & (B); 7(B);	5(O); 6(O ₁); 7(O);			X-20 DYNA- SOAR
	E					M2-F2; HL-10; X-24A; M2-F3	FDL-7; FDL-8
L(3)	O		4(B); 8(O) & (B); 5(B); 12(B); 6(O ₂) & (B); 7(B); 8(B);	5(O); 6(O ₁); 7(O); 9(O)		4(O); 10(O)	11(O) 12(O)
(L/D) _{max} > 5.0	E				(O) - ORBITER; (O ₁) - ONE VERSION OF ORBITER; (O ₂) - SECOND VERSION OF ORBITER (B) - BOOSTER	SV-SJ (JET VERSION OF X-24A)	FDL-7 (WITH SCISSORS WINGS FOR LANDING) FDL-8 (WITH VARIABLE GEOMETRY WINGS)

3. North American Rockwell's Deployable Rotor System
(Reference 13)

North American Rockwell's Deployable Rotor System would return a space craft at a near zero landing speed to dry land touchdowns.

4. Manned Spacecraft Center Reusable Space Shuttle
(Reference 14)

NASA's Manned Spacecraft Center (MSC) design for a reusable space shuttle would use a fixed straight wing design for both the Orbiter and the Booster. The payload capability of the Orbiter would only be 10,000 pounds and it would fit into the Class IV Category because of its medium weight. The Booster, like all the other carriers, would still be classified as a Class III vehicle. Because of the straight wing planform and the onboard propulsion system, the effective subsonic $(L/D)_{\max}$ capability of each vehicle would be greater than 5.0.

5. General Dynamics' Space Shuttle Orbiter (Reference 15)

One of General Dynamics' versions of the Space Shuttle Orbiter would have a cross range capability of 2000 miles at hypersonic speeds.

6. McDonnell Douglas' Space Shuttle Systems (Reference 16)

6

7.

One of the McDonnell Douglas' Space Shuttle Orbiters incorporates drawbridge wings. The wings would remain folded upward against the sides of the fuselage for a large cross-range mission and extended outward for a minimum cross-range mission. With the wings down, a high angle of attack (Faget) re-entry would be made. A different version of the Orbiter would have a delta planform and a cross-range greater than 1,500 nautical miles.

8. North American Rockwell's Space Shuttle Versions
(Reference 17)

8

9.

One design of North American Rockwell's Space Shuttle Orbiter would have a straight wing which would give the Orbiter minimum cross-range capability. The second version would have a delta planform and an $(L/D)_{\max}$ of > 1.5 at hypersonic speeds.

10. Manned Spacecraft Center "DC-3 Shuttle" (Reference 18)

NASA's Manned Spacecraft Center "DC-3 Shuttle" would have a small payload of 15,000 pounds and a very limited cross-range at hypersonic speeds. The Shuttle would have a straight wing and therefore it would fit into the L(3) classification because of its significant $(L/D)_{\max}$ at subsonic speeds.

11. Air Force Flight Dynamics Laboratory's "ILRV" Concepts
& (Reference 19)

12.

Two integral launch/re-entry vehicle (ILRV) configurations, the stage-and-one half expendable tanks and the two-stage fully reusable vehicles would have a high hypersonic $(L/D)_{\max}$. The first configuration consists of a core vehicle which contains all the high cost propulsion systems, etc., plus external propellant tanks. The core vehicle carries about 5 percent of the propellant for the remainder of the boost and to make orbital maneuvers. As soon as the propellant in the drop tanks is expended, the tanks are jettisoned and the core vehicle becomes the shuttle orbiter which eventually makes a horizontal landing.

The two-stage fully reusable configuration would have a winged-body orbit vehicle with a double structure to keep the structural mass fraction as low as possible so that land recovery can be made without sacrificing launch capability.

The classification based on weight and maneuverability and the classification based on cross-range as it relates to hypersonic $(L/D)_{\max}$ may appear to be redundant. The maneuverability coupled with the weight is associated with design load factor as it is related to the vehicle mission. The cross-range as described by hypersonic $(L/D)_{\max}$ is more associated with vehicle performance as it relates to vehicle mission. Attributing high maneuverability to vehicles with high $(L/D)_{\max}$ can be incorrect since maneuverability is traditionally associated with a vehicle's ability to pull g's. Thus it is possible to think of large vehicles with good hypersonic $(L/D)_{\max}$ that would have good cross-range capability but still be limited in their design load factor. All other things being equal, however, an increase in load factor or maneuverability will increase cross-range.

One of the hypersonic $(L/D)_{\max}$ Classes, $(L/D)_{\max} < 0.5$, Class H(1), considered here is essentially ballistic and vehicles in this Class (Mercury, Gemini, Apollo, etc.) are not thought of as lifting re-entry vehicles. This Class is included merely for reference purposes to complete the classification matrix. In terms of hypersonic $(L/D)_{\max}$, lifting re-entry vehicles are

restricted to two Classes, H(2) and H(3), rather than the three classes suggested in Reference 1. By eliminating Class H(1), the grid of Table XVI is reduced by one-third to a smaller matrix of 24 classification categories.

No manned lifting re-entry vehicles presently flying, excluding vehicles with an $(L/D)_{\max} < 0.5$, have ever flown at hypersonic speeds. Because of the lack of adequate information on lifting re-entry missions and tasks at hypersonic speeds, and the lack of experimental data, the specification of flying qualities requirements at hypersonic speeds at this stage in lifting re-entry vehicle development is questionable. If the specification of lifting re-entry vehicle requirements is limited to the present state of the art, such a specification must be confined to terminal glide and landing at low supersonic, transonic, and subsonic speeds. Therefore Classes H(2) and H(3) will not be considered for the present as distinct Classes. It will be considered that handling qualities requirements will be adequately specified if Classification H(2) is combined with Class III and Classification H(3) is considered a part of Class IV. By eliminating H(2) and H(3) as distinct Classes, the classification matrix is reduced to 12 distinct Classes.

A classification based on use appears warranted since most lifting re-entry vehicles that have been designed and built are essentially experimental vehicles. Their mission is to investigate lifting re-entry vehicle concepts and to do research work. The mission and flight envelope of these vehicles are generally more restricted than they would be if the vehicle were to be considered operational. In addition, as an experimental vehicle, a lifting re-entry vehicle will be flown by highly trained and very experienced test pilots under only ideal flight conditions. Thus Level 2 and Level 3 requirements for an operational vehicle may in some cases be acceptable as Level 1 and Level 2 requirements when the vehicle is considered experimental. It is advisable to have minimum flying qualities requirements for experimental vehicles since some of the vehicles built in the future will be considered experimental. It is important to have available handling qualities guide lines for these vehicles in the form of requirements that would be useful in design. It is also important to distinguish between acceptable flying qualities requirements for an experimental, as opposed to an operational, lifting re-entry vehicle with a different mission.

Since the classification of a vehicle as experimental or operational is made on the basis of its specific use, it may be better to treat requirements for an experimental lifting re-entry vehicle like special land- or carrier-based requirements are handled in MIL-F-8785B(ASG) in Section 1.3.1. By not distinguishing between operational and experimental vehicles in the classification scheme of Table XVI, the classification matrix is now reduced to only 6 categories.

A classification scheme based on the terminal glide and landing mode of operation appears to be necessary. The mode of operation is related to the subsonic $(L/D)_{\max}$, and the mode of operation can have considerable impact on the flying qualities requirements. If the vehicle is expected to operate with power during landing, then the subsonic $(L/D)_{\max}$ referred to is the $(L/D)_{\max}$ with power.

All indications are that a vehicle with a subsonic $(L/D)_{\max} < 2.5$ will be unable to perform a successful horizontal landing. Such a vehicle will, in all probability, have a decoupled landing mode such as a deployable rotor or parachute, paraglider wing, etc. for terminal glide and landing. The handling qualities requirements for such vehicles during terminal flight will be quite unique.

A vehicle with $2.5 < (L/D)_{\max} < 5.0$ will require special handling qualities requirements during terminal glide and landing that are different than those of a conventional airplane. Unpowered and underpowered low $(L/D)_{\max}$ vehicles will fit in this category. The M2-F2, M2-F3, HL-10, and X-24A are examples of such vehicles.

A lifting re-entry vehicle with a subsonic $(L/D)_{\max}$ greater than 5.0 is expected to have flying qualities requirements similar to those of conventional airplanes. An $(L/D)_{\max} > 5.0$ may be attainable for a re-entry vehicle if it has fixed unswept wings (Faget concept), variable geometry wings, or power for landing.

Vehicles with a subsonic $(L/D)_{\max} < 2.5$ are considered to operate with a decoupled mode during terminal flight and are not considered within the present state of the art from the standpoint of a flying qualities specification. If the classification of lifting re-entry vehicles is limited to the present state of the art at low supersonic, transonic, and subsonic speeds, the number of classifications in Table XVI can be reduced to the following:

1. Classification Based on Mission as it Relates to Weight Cross-Range, and Load Factor

<u>Class</u>	<u>Description</u>
III	Medium-to-heavy weight, low-to-medium cross-range based on hypersonic $(L/D)_{\max}$ and normal load factor
IV	Small-to-medium weight, medium-to-high cross-range based on hypersonic $(L/D)_{\max}$ and normal load factor

2. Classification Based on Terminal Glide and Landing Mode as it Relates to $(L/D)_{\max}$ at Subsonic Speeds

<u>Class</u>	<u>Description</u>
I(2)	$2.5 < (L/D)_{\max} < 5.0$
I(3)	$(L/D)_{\max} > 5.0$

This classification system is shown as Table XVII. The present and next generation of lifting re-entry vehicles are categorized according to this scheme in the table.

TABLE XVII. Suggested Lifting Re-Entry Vehicle Classification Based on Terminal Flight at Low Supersonic, Transonic and Subsonic Speeds

Classification based on the terminal glide and landing mode	Classification based on mission as it relates to weight, cross-range, and load factor	
	III	IV
	Medium-to-heavy weight, low-to-medium cross-range based on hypersonic $(L/D)_{max}$ and normal load factor	Small-to-medium weight, medium-to-high cross-range based on hypersonic $(L/D)_{max}$ and normal load factor
L(2) $2.5 < (L/D)_{max} < 5.0$	Space Shuttle Booster and Orbiter (Lifting-body without power)	M2-F2, HL-10, X-24A, FDL-7, FDL-8 (all without power)
L(3) $(L/D)_{max} > 5.0$	Space Shuttle Booster and Orbiter (Lifting-body with power) Space Shuttle Booster and Orbiter (Deployable wing or Faget concept with or without power)	FDL-7 with deployable wing FDL-8 with deployable wing M2-F2, HL-10, X-24A, FDL-7, FDL-8, all with power

It is questionable whether the Classification Scheme of Table XVII adequately considers re-entry vehicles with a high angle of attack re-entry ($\alpha \approx 60^\circ$) when this angle of attack is maintained throughout the supersonic, transonic, and into the high subsonic speed region before transition is made to low angles of attack. Faget type re-entry vehicles have been proposed that re-enter in this way. Flying qualities requirements for Faget type Boosters or Orbiters flying under these conditions at low (L/D) 's must be covered by special requirements in the specification.

The reason for including a classification based on $(L/D)_{\max}$ at subsonic speeds during the terminal glide and landing phase of flight is that there are special landing requirements for low $(L/D)_{\max}$ vehicles, especially when such vehicles are unpowered. These requirements are associated with the need for maintaining excess kinetic energy in the approach, that is, an approach speed significantly above stall speed, and the need for executing a precise flare followed by a float period prior to touchdown. Since the effective $(L/D)_{\max}$ can be varied by the use of power, the classification scheme must allow for the use of power during the landing approach to increase the effective $(L/D)_{\max}$ and reduce the glide angle. In fact, if landing approach requirements of unpowered or underpowered lifting re-entry vehicles can be related to some simple landing approach handling qualities parameters, and particular requirements on these parameters, it will not be necessary to designate vehicles with a low $(L/D)_{\max}$ at subsonic speeds as a special Class. This procedure is followed in this lifting re-entry vehicle handling qualities specification. In this event, the classification scheme of Table XVII can be reduced to only two Classes as follows:

Class III: Medium-to-heavy weight, low-to-medium cross-range based on hypersonic $(L/D)_{\max}$ and normal load factor

Class IV: Light-to-medium weight, medium-to-high cross-range based on hypersonic $(L/D)_{\max}$ and normal load factor.

The Roman numerals III and IV were used to designate these two lifting re-entry vehicle Classes since they are most comparable to Classes III and IV in MIL-F-8785B(ASG). Based on the discussion presented, it becomes readily apparent why the Scope, Application, Classification of Vehicles, and Operational or Experimental Designation Sections are defined as indicated in Section II.

Although this specification will be limited to flying qualities requirements at low supersonic, transonic, and subsonic speeds, it is the intention that in the future these requirements will be extended to flight at hypersonic speeds, including flight at low dynamic pressures. The two Classes can then be easily extended to four Classes based on cross-range as determined by hypersonic $(L/D)_{\max}$. This classification scheme is indicated in Table XVIII.

Requirement

1.4 Flight Phase Categories

Discussion

Experience with the operation of airplanes indicates that certain Flight Phases are more demanding and require better handling qualities than others. Therefore, where possible, handling qualities requirements are stated in terms of Flight Phases as well as airplane Class.

TABLE XVIII. Suggested Lifting Re-Entry Vehicle Classifications at all Flight Speeds

Classification based on cross-range as determined by hypersonic $(L/D)_{\max}$	Classification based on weight and maneuverability	
	III	IV
	Medium-to-heavy weight, low-to-medium maneuverability based on load factor	Small-to-medium weight, medium-to-high maneuverability based on load factor
$H(2)$ $0.5 < (L/D)_{\max} < 1.5$		
$H(3)$ $(L/D)_{\max} > 1.5$		

Piloting experience with lifting re-entry vehicles is extremely limited but the experience that does exist supports the idea of specifying flying qualities requirements as a function of Flight Phases, at least for terminal flight at low supersonic, transonic, and subsonic speeds. This experience, interestingly enough, also appears to support the idea that these Flight Phases can at least be broadly categorized as Nonterminal Flight Phases and Terminal Flight Phases. All of this should not be surprising since, during terminal flight, re-entry vehicles will fly under similar environmental conditions and the piloting tasks will be similar to those of airplanes.

The Nonterminal Flight Phases of re-entry vehicles appear to lend themselves to two categories, A and B, as is true for Nonterminal Flight Phase categories of airplanes as presented in MIL-F-8785B(ASG). It is also true that the grouping of re-entry vehicle Flight Phases in the various Categories, except for Category A, bear a striking resemblance to the classification of Flight Phases for conventional airplanes. But from here on, the similarities between Flight Phase Categories of re-entry vehicles and airplanes appear to cease.

The most demanding Flight Phases for airplanes are Category A Flight Phases. They require rapid maneuvering, precise tracking, or precise flight path control. Present experience with lifting re-entry vehicles, through actual flight and simulation, does not support the need for rapid maneuvering or very precise tracking. The most demanding Flight Phases appear to be

Category C Terminal Flight Phases that require precise flight-path control and may require rapid maneuvering, but certainly not as rapid maneuvering as Category A Flight Phases for conventional airplanes.

Category A Flight Phases for re-entry vehicles bear no resemblance to Category A Flight Phases for conventional airplanes primarily because of the difference in the missions of re-entry vehicles and airplanes. Category A Flight Phase for re-entry vehicles require precise but only moderate maneuvering and accurate flight-path control and precise tracking may be required, such as tracking or maintaining angle of attack or bank angle, but the rapidity of maneuvering associated with tracking or attitude and bank angle control is not expected to be comparable to Category A Flight Phases for airplanes or Category C Flight Phases for re-entry vehicles.

Category B Flight Phases for re-entry vehicles are expected to be the least demanding for re-entry vehicles as is true of Category B Flight Phases for airplanes. In the case of re-entry vehicles, these Flight Phases are normally accomplished using gradual maneuvers without precision tracking or very accurate flight-path control.

An explanation of some of the Flight Phases for re-entry vehicles, and why they are placed in particular Flight Phase Categories is in order.

Air launch and powered boost Category A Flight Phases are valid for experimental lifting re-entry vehicles such as the M2-F2, HL-10, X-24A, and M2-F3. It would appear that moderate maneuvering and accurate flight path control and precise tracking may be required. The requirements in this specification are not expected to apply to multi-stage vehicles while they are attached during boost. Powered boost of multi-stage vehicles is not a Flight Phase within the limitations of this specification. In discussions with some participants in review meetings, some sentiment was expressed that high Mach number high altitude cruise, based on experience with the XB-70 and SR-71, can be a more demanding Flight Phase than cruise at lower altitudes and speeds. This appears to be especially true when trying to control flight path and altitude. High altitude, high speed cruise is therefore included as a Category A Flight Phase even though its validity as a lifting re-entry vehicle Flight Phase is questionable. It seemed appropriate that large angle of attack transitions that are presently being considered for the Space Shuttle Vehicle Booster and Orbiter vehicles would logically fall into Category A Flight Phases when they are being performed with the pilot in the loop. They will probably require precise altitude and flight path control.

Category B Flight Phases for re-entry vehicles are similar to Category B Flight Phases for airplanes and appear to require no further explanation.

Category C Flight Phases for re-entry vehicles are generally similar to Category C Flight Phases for airplanes. As operational vehicles, lifting re-entry vehicles are expected to be launched vertically with one and one-half

or more stages. As previously stated, under such conditions of attached stages these requirements are not expected to apply. As experimental vehicles, it may be that Booster and Orbiter stages of re-entry vehicles will first be tested in the lower atmosphere and they will be required to take off horizontally from the ground. Under such conditions a conventional horizontal takeoff is a valid Flight Phase. Emergency abort is also a valid Terminal Phase for any stage of a multistage vehicle when it flies alone following an abort that occurs in the lower atmosphere at low supersonic, transonic and subsonic speeds. Pilot controlled emergency aborts will require precise flight path control and rapid maneuvering.

Requirement

1.5 Levels of flying qualities

Discussion

The Definitions of Levels that are used in specifying handling qualities requirements for lifting re-entry vehicles are essentially the same as the definitions in Section 1.5 of MIL-F-8785B(ASG) (Reference 2). The explanation of how these Levels are used and how they are related to the pilot rating scale are presented in Reference 8.

A slight difference exists in the definition of Level 3 for lifting re-entry vehicles. In the definition of Level 3 for conventional airplanes it is stated that "Category A Flight Phases can be terminated safely, and Categories B and C Flight Phases can be completed." In the case of re-entry vehicles this statement becomes "All Flight Phases that can be terminated can be safely terminated. All Flight Phases that must be completed can be completed safely."

Although all Category A Flight Phases for airplanes in MIL-F-8785B(ASG) can be terminated, such is not the case for all Category A Flight Phases for re-entry vehicles. Phases such as "air launch" or "angle of attack transition" once started must be completed. In the case of Category B Flight Phases for re-entry vehicles, some of the Flight Phases must be completed. In the case of Category C, all Flight Phases must be completed with the possible exception of a powered approach. It is generally true that for the Terminal Flight Phases of re-entry vehicles without power, all the Flight Phases must be completed and completed safely for Level 3.

Serious thought is presently being given to the design of very sophisticated lifting re-entry vehicles that are expected to be operational vehicles that will be required to fly the total flight profile from boost to orbit to re-entry and horizontal landing. Reliability requirements for the various stages of such a vehicle and all the subsystems will be high because of high program and vehicle costs, the environmental unknowns, and the requirement for crew and passenger safety. Reliability and safety considerations may be such that the procuring activity may choose not to allow Level 3 handling qualities. If such is the case the probability of occurrence of Level 3 handling qualities due to failures will also need to be reduced considerably as indicated in 3.1.10.2.

Requirement

2.0 Applicable documents

Discussion

In the specification of the flying qualities of airplanes in MIL-F-8785B(ASG) it is felt necessary to refer to other documents in presenting the specific requirements. To the extent that lifting re-entry vehicles fly like conventional airplanes during terminal flight at low supersonic, transonic, and subsonic speeds, these documents are also likely to be applicable to lifting re-entry vehicles with corrections, deletions, and additions that may be required and will be established by the procuring activity. Because of the many undefined aspects of lifting re-entry vehicle design, it is difficult to establish at this time what, if any, corrections, deletions, and additions must be made in these specifications. If the contractor finds particular specifications not applicable in their present form, the necessary corrections, deletions, or additions must be established through mutual consultation between the contractor and the procuring activity.

MIL-D-8708 (Demonstration Requirements for Airplanes) has been removed entirely as a specification since it is not expected to be applicable to lifting re-entry vehicles.

The procuring activity may find it necessary to establish special specifications and standards for lifting re-entry vehicles that will replace or supplement existing standards. To the extent that such standards relate to handling qualities requirements they will become a part of this specification.

Requirements

3.0 Requirements

3.1 General requirements

3.1.1 Missions

3.1.2 Loadings

3.1.3 Moments of inertia

3.1.4 External stores

3.1.5 Configurations

Discussion

The need to define missions, loadings and envelopes of center of gravity travel, moments of inertia, external store loadings, and vehicle configurations required to perform the missions seem obvious. These requirements

are expected to be equally applicable to lifting re-entry vehicles and airplanes although many of the details in such definitions will undoubtedly be different for lifting re-entry vehicles whose missions are different than those of airplanes. In the definition of missions, differences will also exist when the vehicle is to be considered operational or experimental.

In the definition configurations for lifting re-entry vehicles, it is recognized that in all probability such vehicles will be highly augmented and it is emphasized that SAS gains may be variable and selected by the pilot or crew. Obviously such SAS gains are part of the configuration definition. It is also true that longitudinal and lateral-directional control bias, other than that required for trim, may also be essential to configuration definition. These additional requirements for configuration definition may be especially applicable to an experimental lifting re-entry vehicle.

Requirements

- 3.1.6 State of the vehicle
- 3.1.6.1 Vehicle Normal States
- 3.1.6.2 Vehicle Failure States
- 3.1.6.2.1 Vehicle Special Failure States

Discussion

The purpose and need for defining lifting re-entry vehicle states including Vehicle Normal States, Vehicle Failure States, and Vehicle Special Failure States appear to be equally valid for a re-entry vehicle or an airplane. The requirements in the specification of handling qualities are therefore logically related to re-entry vehicle states, Normal States and Failure States. The discussion pertaining to Airplane States that appears in Reference 8 is expected to be equally valid for re-entry vehicles.

In 3.1.6.2 an additional qualification has been added that the contractor may waive definition of all Vehicle Failure States for experimental vehicles. It is recognized that a definition of all Failure States and probability of failures can be very difficult and expensive for low budget, "one of a kind," experimental vehicles. It is recognized that in such cases, a simplified yet acceptable alternate way of specifying Failure States may be acceptable to the procuring activity.

There are certain Failure States, such as engine failures, that may be perfectly acceptable as Special Failure States for airplanes. Engine failures, or failure of an engine to start, in certain Flight Phases of a lifting re-entry vehicle, may result in handling qualities that make the vehicle extremely difficult to fly or unflyable. Such may be the case for a lifting re-entry vehicle whose $(L/D)_{\max}$ unpowered is so low that it requires

an "instant (L/D)" or landing engine to perform a horizontal landing. Even though the failure probability of the engine to start or continue to operate may be difficult to predict, the remoteness of the probability of failure is extremely important even though the probability is not well known. In such cases, it can be argued that engine failures should not be acceptable as Special Failure States and the paragraph on Special Failure States should exclude such engine failure for vehicles with a low $(L/D)_{\max}$ without power. The contractor in such cases should be required to determine the probability of failure or through adequate redundancy give assurance to the procuring activity that the probability of failure is indeed remote. Since little actual experience exists in this area for lifting re-entry vehicles, it is left to the discretion of the procuring activity whether such engine failures can or cannot be considered as Special Failure States.

Requirements

3.1.7 Operational Flight Envelopes

3.1.8 Service Flight Envelopes

3.1.8.1 Maximum service speed

3.1.8.2 Minimum service speed

3.1.8.3 Maximum service altitude

3.1.8.4 Service load factors

Discussion

The definitions of Operational Flight Envelopes and Service Flight Envelopes for lifting re-entry vehicles follow the basic philosophy used in defining Operational and Service Flight Envelopes of airplanes in MIL-F-8785B (ASG). It is recognized, however, that Operational Flight Envelope boundaries for lifting re-entry vehicles may be more conveniently or adequately defined in other ways than speed, altitude, and load factor for particular Flight Phases. Load factor and speed may not always be the important controlling parameters during re-entry, or the terminal phase of re-entry. Mach number, dynamic pressure, or angle of attack may be more important parameters from the standpoint of longitudinal deceleration, temperature, or stability. This may be especially the case when the re-entry vehicle is unpowered. These parameters may also be more appropriate in defining the boundaries of the Service Flight Envelopes for the same reasons.

It is recognized that the Operational and Service Flight Envelopes of an experimental lifting re-entry vehicle can differ from those of an operational vehicle. If a lifting re-entry vehicle is to be considered experimental the procuring activity may be willing to accept more restricted Operational and Service Flight Envelopes.

Definition "c" in Section 3.1.8.1 recognizes that the vehicle maximum service speed may be determined by the fact that the vehicle is unpowered. Definition "d" recognizes that a maximum service speed may be defined by engine limitations.

It is also recognized that additional conditions exist which may define minimum service speed for a lifting re-entry vehicle. Minimum speed for unpowered lifting re-entry vehicles must be defined in gliding flight. Definition "e" recognizes that safe unpowered landings with lifting re-entry vehicles require excess kinetic energy. Thus unpowered landing requirements may determine the minimum service speeds at low altitudes. Definition "f" recognizes that some lifting re-entry vehicle configurations have no clearly defined stall. If sufficient control power exists, the vehicle may be trimmable to rather large angles of attack where the $(L/D)_{\max}$ is low. An unpowered vehicle trimmed at such large angles of attack in gliding flight, especially at the lower altitudes, may have an excessive sink rate or steep glide angle which may determine the minimum service speed.

For Flight Phases at altitude for some re-entry vehicles, minimum and maximum service speed may not be as meaningful as minimum and maximum dynamic pressure as a function of altitude. Thus minimum and maximum dynamic pressure may be used in lieu of minimum and maximum service speed with the approval of the procuring activity provided that the maximum dynamic pressure is less and the minimum dynamic pressure is greater than the dynamic pressures computed using the maximum or minimum service speed respectively.

The maximum service altitude of a vehicle with power that is capable of cruising in level flight is reasonably easy to define. It can be defined in the same way that the maximum service altitude of an airplane is defined. For an unpowered re-entry vehicle which is truly operational, which has re-entered from orbital altitudes where the dynamic pressure for all practical purposes is zero, defining maximum service altitude is not meaningful.

It has been stated in the Introduction (Section I), that the requirements of this specification are expected to apply only when the vehicle is sustained by primarily aerodynamic forces. It has been suggested that below dynamic pressures equal to 0.7 times the dynamic pressure required to sustain the vehicle in level flight may be considered as a minimum dynamic pressure below which these handling qualities are not expected to apply. Based on this definition, a maximum service altitude may be defined as the altitude above which the dynamic pressure is less than 0.7 times the minimum service speed dynamic pressure as defined by the minimum service speed of 3.1.8.2.

Since this specification is only expected to apply to low supersonic, transonic, and subsonic speeds during terminal flight in the lower atmosphere, it may be necessary to define a maximum service altitude for purposes of applying this specification. This altitude will be established by mutual agreement between the contractor and the procuring activity.

The service load factors for re-entry vehicles are defined in essentially the same way as they are for airplanes in MIL-F-8785B(ASG), except for an unpowered vehicle they are defined in equilibrium glide flight at constant indicated airspeed. In the case of re-entry vehicle configurations, a clear stall warning angle or buffet angle of attack may not exist and the load factors may be defined by a maximum (minimum) allowable angle of attack defined by considerations such as those in 3.4.2.2.

Requirements

3.1.9 Permissible Flight Envelopes

3.1.9.1 Maximum permissible speed (minimum permissible angle of attack)

3.1.9.2 Minimum permissible speed (maximum permissible angle of attack)

3.1.9.2.1 Minimum permissible speed (maximum permissible angle of attack) based on other considerations

Discussion

The rationale for defining Permissible Flight Envelopes for lifting re-entry vehicles is similar to that used for airplanes in MIL-F-8785B(ASG). There are regions outside the Operational and Service Flight Envelopes where lifting re-entry vehicles might be allowed to operate for short periods of time and one would not expect Level 1 or Level 2 handling qualities to prevail. Although stalls may be such a region for lifting re-entry vehicles, one can see no rational reason at this time why spins, zooms, or steep dives need be considered as permissible flight conditions for re-entry vehicles as may be true of airplanes. High angle-of-attack flight may, however, be such a flight condition for a re-entry vehicle. Again, the boundaries of the Permissible Flight Envelopes for re-entry vehicles at altitude during some Flight Phases may be defined more meaningfully in terms of such parameters as dynamic pressure and angle of attack rather than speed and load factor.

It is recognized that unpowered lifting re-entry vehicles must be capable of performing unpowered landings. Such landings can only be performed safely within certain maximum or minimum speed limits. The minimum speed limit is determined by having sufficient kinetic energy available to perform a safe flare and float to touchdown. Thus maximum and minimum permissible speeds determined by landing requirements are appropriate for unpowered lifting re-entry vehicles.

Lifting re-entry vehicles have both static and dynamic stability and control characteristics which are usually strong functions of angle of attack. In some cases, even with augmented vehicles, the stability and control characteristics from the point of view of handling qualities can be unacceptable below or above particular angles of attack. Thus maximum permissible speed

(minimum permissible angle of attack) or minimum permissible speed (maximum permissible angle of attack) may be determined by unsafe stability and control characteristics.

Minimum permissible speed (maximum permissible angle of attack) for lifting re-entry vehicles can also be determined by other considerations such as ability to perform altitude corrections, excessive sink rate, too steep an equilibrium glide angle, etc.

Requirements

3.1.10 Application of Levels

3.1.10.1 Requirements for Vehicle Normal States

3.1.10.2 Requirements for Vehicle Failure States

3.1.10.2.1 Requirements on the effects of specific failures

3.1.10.3 Exceptions

3.1.10.3.1 Ground operation and terminal Flight Phases

3.1.10.3.2 When Levels are not specified

3.1.10.3.3 Flight outside the Service Flight Envelopes

Discussion

The Level approach to the achievement of adequate flying qualities with a degradation of flying qualities being acceptable, if the combined probability of such degradation is sufficiently small, is rational and appears reasonable for lifting re-entry vehicles as well as airplanes. Flying qualities, flight safety, and system reliability are very interrelated. It is obvious that such interrelationships should be recognized in the specification of handling qualities requirements.

The basic approach used in the application of Levels to airplanes in MIL-F-8785B(ASG) is retained in the specification of handling qualities requirements for lifting re-entry vehicles. The argument for the Level concept and its application presented in Reference 8 are in general equally applicable to lifting re-entry vehicles. It is recognized in Reference 8 that the procuring activity can change the numerical probability per flight of encountering degraded Levels, Levels 2 and 3, of flying qualities due to failures. These changes are made to reflect specific vehicle requirements and to assure that the probabilities of encountering degraded Levels are consistent with the design goals. Although the degraded Level probabilities per flight as presented are reasonable, an attempt has been made in this specification to reflect the possible differences in the design goals of various lifting re-entry vehicles.

For "one of a kind", low budget, experimental lifting re-entry vehicles, detailed determination of each Vehicle Failure State, the probability of occurrence of each vehicle failure per flight, and the effect of such Failure States on the flying qualities may be both impractical and impossible for the contractor. In lieu of such determination, a simplified procedure is allowed for experimental lifting re-entry vehicles. One procedure is to consider only a very limited number of critical failures and their effect on flying qualities and simultaneously reduce the probability of the occurrence of degraded flying qualities due to such critical failures. Another alternate method may be to associate degraded Levels with total system failures, such as total SAS system failure and not be required to predict the probability of encountering degraded Levels. Such alternate procedures seem warranted for "one of a kind", low budget, experimental vehicles and such alternate procedures are not considered inconsistent with MIL-F-8785B(ASG).

Similar arguments in terms of vehicle design goals can be used to reduce the probability per flight of encountering degraded flying qualities because of failures. Serious thought is presently being given to the design of very sophisticated lifting re-entry vehicles, such as the Space Shuttle Vehicle (SSV) Booster and Orbiter. Such vehicles will be required to fly the total flight profile from boost to orbital flight, through re-entry and down to a horizontal landing. Reliability requirements for the various stages of such a vehicle and its subsystems will be high. The feeling presently is that any flight control system will be required to first fail operationally two times without any degradation in handling qualities and the third failure will be fail safe, safe to fly home. Such high reliability requirements are considered necessary because of high program and vehicle costs, the environmental unknowns, and the overriding requirement for crew and passenger safety. It is also felt that the reliability requirements for guidance and navigation, which is essential to successful flight, automatic or piloted, allow for high total systems reliability at relatively little additional cost. When all of these factors are overriding considerations in lifting re-entry vehicle design, the procuring activity may choose to reduce the probability of encountering degraded flying qualities because of failures, even to the extent of not allowing Level 3 handling qualities at all. Obviously for such to be the case, the probability of occurrence of Level 3 per flight must be quite small. In one such preliminary handling qualities specification for the SSV proposed by the NASA Flight Research Center at Edwards, California, it has been suggested that the probability of occurrence of Level 3 for flight should be less than 10^{-6} since this low a probability would essentially eliminate Level 3 as a consideration.

In Reference 8 arguments and data are presented, based on certain assumptions, to confirm that the probability of encountering Level 3 handling qualities of 10^{-4} per flight is reasonable for aircraft. It is argued that "due to a lack of knowledge,---especially when many flying qualities are degraded at once, the Level 3 boundaries are at least safety related" even though Level 3 handling qualities are not considered unsafe as they are usually defined. Using 1967 accident loss rates for aircraft, and assuming

"Level 3 to represent a safety problem, which it conservatively does not, then the allowable 10^{-4} probability of encountering Level 3 per flight would account for about 1/4 to 1/9 of the total probability of aircraft loss--" during 1967. The other aircraft losses would be due to other things that are not flying qualities oriented. It is therefore argued that the 10^{-4} probability for Level 3 is reasonable.

Using the same data and arguments presented in Reference 8, a 10^{-6} probability of encountering Level 3 per flight would conservatively account for only 1/400 to 1/900 of the aircraft loss during 1967. It seems reasonable to assume that such a low probability of encountering Level 3 for aircraft or lifting re-entry vehicles will essentially eliminate Level 3 as a probability.

Requirement

3.2 Longitudinal flying qualities

Discussion

Section 3.2 deals with essentially the same longitudinal flying qualities subjects treated for airplanes in MIL-F-8785B(ASG). This should not be surprising since lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds are expected to fly much like conventional airplanes and require similar characteristics from the point of view of handling qualities. Modifications have been made to specific requirements, in some cases significant modifications, to make the requirements more adaptable to the Flight Phases of lifting re-entry vehicles. These changes are discussed in some detail as they arise. Some very special and new requirements that are unique to lifting re-entry vehicles have been added. Section 3.2.1.1.3 presents some qualitative requirements on elevator control force variations during angle of attack transitions. Section 3.2.3.3.1, "Longitudinal control in catapult takeoff" in MIL-F-8785B(ASG), has been replaced by a requirement called "longitudinal control during air launch". Section 3.2.3.4.2 covers a completely new requirement for unpowered landings. Section 3.2.3.4.3 is a new qualitative requirement on the effects of adverse elevator lift during the Landing Approach Flight Phase.

Requirements

3.2.1 Longitudinal stability with respect to speed

3.2.1.1 Longitudinal trim stability

Discussion

In MIL-F-8785B(ASG), requirements under Section 3.2.1 are spoken of as longitudinal stability requirements with respect to speed and deal primarily with long term requirements as the speed is varied in level flight. These topics are discussed in the airplane flying qualities specification as static stability, phugoid stability, and flight-path stability. There is some

question as to how important these long term stability requirements are to a lifting re-entry vehicle during terminal descent to a horizontal landing when the pilot will undoubtedly be controlling the vehicle rather attentively. There is also some question of the meaning of long term requirements and how they are defined when the vehicle is operating in a rapidly changing environment of altitude, Mach number, etc. There is ample evidence based on flight test experience with unpowered landings of lifting re-entry vehicles that flight-path stability is of importance to the pilot. Providing some long term stability, or at least limiting the degree of instability, is expected to improve lifting re-entry vehicle handling qualities in much the same manner that handling qualities of airplanes are improved. Thus the rationale and data on speed stability used to develop requirements in MIL-F-8785B(ASG) should apply to lifting re-entry vehicles with some modification to make the requirements applicable to lifting re-entry Vehicle Flight Phases.

Section 3.2.1.1 which is identified as "Longitudinal static stability" in MIL-F-8785B(ASG) is identified simply as "Longitudinal trim stability" in the case of lifting re-entry vehicles. This was done to overcome any misunderstanding that the requirement does in fact measure static stability, that is, the slope of the pitching moment with angle of attack, independent of other factors. It also does not measure pitching moment variation with Mach number, neutral point location, etc. This is especially true of lifting re-entry vehicles that will spend much of the terminal phase of flight in gliding turns or simply gliding flight. All of the characteristics just described certainly do influence the tendency of the vehicle to diverge from or return to trim. However, it would be difficult to isolate the effect of each characteristic on the basic stability conditions of the vehicle without performing a lengthy test program. The important consideration in this requirement is not what specific characteristics caused the vehicle to react in the way it does, but the overall trim characteristics of the vehicle with changes in airspeed and the tendency of the speed to diverge aperiodically. It is these characteristics that the requirement specifies.

The requirement follows the requirement for airplanes in MIL-F-8785B(ASG) with some modifications. In terminal gliding flight, indicated airspeed will be a more representative primary flight control variable than equivalent airspeed. In certain Flight Phases of a re-entry vehicle, dynamic pressure or angle of attack changes in gliding flight may be the primary flight parameter and either of these may be used in lieu of airspeed.

For Level 3, an aperiodic divergence of the incremental speed or other flight variable from trim is permitted provided the time to double amplitude is at least 60 seconds. As shown in References 20, 21, 22, 23, and 24, a certain amount of instability can be allowed for Level 3. Based on this data, and the fact that the pilot will be generally maintaining tight control over the vehicle during terminal flight, a slight aperiodic divergence in speed appears reasonable.

Requirements

- 3.2.1.1.1 Relaxation in transonic flight
- 3.2.1.1.2 Elevator control force variations during rapid speed or Mach number changes
- 3.2.1.1.3 Elevator control force variations during angle of attack transitions

Discussion

The relaxation in speed stability requirements in the transonic region follows essentially a similar relaxation in MIL-F-8785B(ASG). The use of equilibrium trim dynamic pressure or angle of attack is permissible as the primary flight variable rather than speed for certain transonic Flight Phases of a re-entry vehicle where these variables are more meaningful. Relaxation is allowed for more prolonged transonic flight of an experimental vehicle with the approval of the procuring activity. A greater relaxation seems reasonable for a vehicle which is primarily intended for an experimental mission, but the degree of relaxation is left to be defined by the procuring activity.

The requirements in 3.2.1.1.2 during rapid speed or Mach number changes are similar for airplanes and re-entry vehicles for much the same reasons. In the case of lifting re-entry vehicles, these rapid trim changes may be associated with large and rapid dynamic pressure or angle of attack changes.

Some lifting re-entry vehicles that are presently under study are expected to re-enter the atmosphere at large angles of attack, as high as 60 degrees, and perform an angle of attack transition before terminal flight glide prior to landing. This has been described as a pitchover and pullout maneuver. A simulator study of such a maneuver is described in some detail in Reference 25. The study indicates that such a maneuver can be performed by the pilot, but the results are too preliminary to establish general requirements. A qualitative requirement such as that presented as 3.2.1.1.3 is, however, in order. It is hoped that in the future a quantitative requirement can be developed.

Requirements

- 3.2.1.2 Phugoid stability
- 3.2.1.3 Flight-path stability

Discussion

As stated in Reference 8, "Although pilots can handle airplanes having poor phugoid damping, they will make such comments as: the airplane 'requires

constant attention,' 'is frustrating to fly,' and 'is difficult to trim'." Because of its nuisance value, if for no other reason, it is desirable to have some slight phugoid stability or to at least limit the degree of instability for some vehicles and some levels.

For an operational lifting re-entry vehicle, the requirements of MIL-F-8785B(ASG) appear to be as valid for lifting re-entry vehicles as for airplanes. The discussion in Reference 8 that substantiates these requirements, even though the requirements are admittedly conservative, should also apply to lifting re-entry vehicles. Data from Reference 26 suggests more lenient phugoid requirements than those in MIL-F-8785B(ASG). It should be possible to allow more lenient phugoid requirements for experimental vehicles than those shown in 3.2.1.2. Experimental vehicles will be flown under more ideal flight conditions by very experienced pilots. Although the data in Reference 8 appears to support the idea of more lenient phugoid requirements, it is difficult, based on the available data, to establish reasonable boundaries for an experimental lifting re-entry vehicle.

For purposes of analyzing phugoid motions, especially at high speeds, it should be understood that altitude changes and density gradients with altitude will affect the phugoid characteristics. These effects on phugoid characteristics are summarized at all flight velocities up to orbital velocities in Reference 27. Reference 28 should also be consulted for these effects at velocities applicable during the terminal Flight Phase of re-entry at low supersonic, transonic, and subsonic speeds.

There is ample evidence to indicate that operation on the "backside" of the drag curve can lead to problems in control of airspeed and flight-path angle. For a powered vehicle this is also spoken of as operation on the "backside" of the "power required" curve. For an unpowered vehicle in landing approach, it is also spoken of as the "backside" of the L/D curve.

The data upon which the requirements of MIL-F-8785B(ASG) are based are presented in Reference 8 and there is every reason to believe that these data are equally valid for powered lifting re-entry vehicles in the landing approach. Although flight-path instability is allowed for powered vehicles, there is little evidence to indicate that flight-path instability should be allowed for unpowered approaches of lifting re-entry vehicles. In fact, flight test experience from high energy landing approaches of airplanes and lifting re-entry vehicles tend to support the idea that pilots need some flight-path stability and will fly unpowered vehicles, especially low $(L/D)_{max}$ vehicles at sufficiently high approach velocities so that frontside operation is assured during the entire approach to touchdown (References 29, 30, 31, 32, 33, 34, and 35). Based on these results, and the present opinions of those experienced with unpowered landing at Edwards, California, it has been decided to require that the flight-path angle versus indicated airspeed shall have a negative local slope at all speeds greater than the vehicle operational touchdown speed minus 5 knots.

Feelings have been expressed by some in the field of lifting re-entry vehicle design that some "backside" operation can be safely allowed for unpowered vehicles during the float period or following the flare. Unfortunately, insufficient information exists at present on the degree of flight-path stability or instability that is acceptable during the flare and float. For an unpowered vehicle, drag modulation in the form of spoilers or drag brakes is very desirable and would undoubtedly have an influence on the amount of "backside" operation that a pilot can tolerate in the flare and float.

Suggestions have been made that $d\gamma/d\omega$ limits are not necessarily an adequate specification of flight-path control requirements in the landing approach. It has been suggested that other factors may influence the problem such as pitch attitude control, since the pilot first commands pitch-attitude changes with the elevator, and flight-path angle and velocity changes result from the commanded pitch-attitude change. In this connection, it may be instructive to look at the gains and time constants in the various longitudinal transfer functions that may be important during the landing approach.

Assuming that the force damping terms of the vehicle are negligibly small and the lift and drag derivatives of the elevator used for longitudinal control are negligibly small, it is possible to obtain the following longitudinal transfer functions for elevator control inputs:

$$\frac{u(s)}{\delta_e(s)} = \frac{K_{u\delta_e} \left(s + \frac{1}{\tau_{u_1}} \right)}{(s^2 + 2\zeta_p \omega_{np} s + \omega_{np}^2)(s^2 + 2\zeta_{sp} \omega_{nsp} s + \omega_{nsp}^2)} \quad (3)$$

$$\frac{\theta(s)}{\delta_e(s)} = \frac{K_{\theta\delta_e} \left(s + \frac{1}{\tau_{\theta_1}} \right) \left(s + \frac{1}{\tau_{\theta_2}} \right)}{(s^2 + 2\zeta_p \omega_{np} s + \omega_{np}^2)(s^2 + 2\zeta_{sp} \omega_{nsp} s + \omega_{nsp}^2)} \quad (4)$$

$$\frac{\gamma(s)}{\delta_e(s)} = \frac{K_{\gamma\delta_e} \left(s + \frac{1}{\tau_{\gamma_1}} \right)}{(s^2 + 2\zeta_p \omega_{np} s + \omega_{np}^2)(s^2 + 2\zeta_{sp} \omega_{nsp} s + \omega_{nsp}^2)} \quad (5)$$

$$\frac{\dot{h}(s)}{\delta_e(s)} = \frac{K_{h\delta_e} \left(s + \frac{1}{\tau_{h_1}} \right)}{(s^2 + 2\zeta_p \omega_{np} s + \omega_{np}^2)(s^2 + 2\zeta_{sp} \omega_{nsp} s + \omega_{nsp}^2)} \quad (6)$$

If it is further assumed that the initial flight-path angle is sufficiently small so that terms containing $\sin(\gamma_0)$ can be dropped and $\cos(\gamma_0)$ can be made equal to one, it is possible to approximate the terms in these transfer

functions as indicated below. It is of course recognized that assuming $\sin(\gamma_0)$ to be small is not necessarily a good assumption for unpowered low $(L/D)_{\max}$ vehicles.

$$2\gamma_p \omega_{np} \approx -X_u$$

$$\omega_{np}^2 \approx -\frac{g}{V_0} Z_u$$

$$2\gamma_{sp} \omega_{nsp} \approx -(M_{\dot{u}} + M_q + Z_w)$$

$$\omega_{nsp}^2 \approx -(M_{\dot{u}} - M_q Z_w)$$

$$K_{u\delta_e} \approx V_0 \left(Z_w - \frac{g}{V_0} \right) M_{\delta_e}$$

$$\frac{1}{\tau_{u_1}} \approx \frac{\frac{g}{V_0} Z_w}{\left(X_w - \frac{g}{V_0} \right)}$$

$$K_{o\delta_e} \approx M_{\delta_e}$$

$$\frac{1}{\tau_{o_1}} \approx -Z_w$$

$$\frac{1}{\tau_{\theta_1}} \approx -X_u + X_w \frac{Z_u}{Z_w}$$

$$K_{\gamma\delta_e} \approx -Z_w M_{\delta_e}$$

$$\frac{1}{\tau_{\gamma_1}} \approx -X_u + \left(X_w - \frac{g}{V_0} \right) \frac{Z_u}{Z_w}$$

$$K_{h\delta_e} \approx -V_0 Z_w M_{\delta_e}$$

$$\frac{1}{\tau_{h_1}} \approx -X_u + \left(X_w - \frac{g}{V_0} \right) \frac{Z_u}{Z_w}$$

$$\frac{d\gamma}{du} \approx \frac{1}{g} \left[-X_u + \left(X_w - \frac{g_0}{V_0} \right) \frac{Z_u}{Z_w} \right]$$

It is interesting to note that many of the time constants are strongly interrelated through the derivatives and do not necessarily vary independently of one another. It can easily be established that

$$\frac{d\sigma}{du} = -\frac{1}{g} \frac{1}{\tau_{h_1}} = -\frac{1}{g} \frac{1}{\tau_{\sigma_1}} = -\frac{1}{g} \frac{1}{\tau_{\sigma_0}} + \frac{1}{V_0} \frac{Z_u}{Z_w} \quad (7)$$

The last terms, $Z_u/V_0 Z_w$, can be related to the phugoid frequency and Z_w . Equation 7 now becomes

$$\frac{d\sigma}{du} = -\frac{1}{g} \frac{1}{\tau_{h_1}} = -\frac{1}{g} \frac{1}{\tau_{\sigma_1}} = -\frac{1}{g} \left(\frac{1}{\tau_{\sigma_0}} + \frac{\omega_{np}^2}{Z_w} \right) \quad (8)$$

It is obvious from this relationship that $1/\tau_{h_1}$ and $1/\tau_{\sigma_1}$ are the same and differ from $d\sigma/du$ by only a constant, $-1/g$. At zero phugoid frequency, $1/\tau_{\sigma_0}$ is identical to $1/\tau_{h_1}$ and $1/\tau_{\sigma_1}$, and it also differs from $d\sigma/du$ by the same constant. The only way that $1/\tau_{\sigma_0}$ can be varied independently of $d\sigma/du$ is through the phugoid frequency and Z_w . When the phugoid frequency is small, the term ω_{np}^2/Z_w is likely to be negligibly small.

In spite of the assumptions made in the approximation of the parameters discussed, it is likely to be true that these parameters are not independent but highly functionally related. Variations in $d\sigma/du$ imply highly functional variations in $1/\tau_{h_1}$, $1/\tau_{\sigma_1}$, and $1/\tau_{\sigma_0}$, and the independent effects of these parameters on flight-path control are likely to be small.

Requirements

3.2.2 Longitudinal maneuvering characteristics

3.2.2.1 Short-period response

3.2.2.1.1 Short-period frequency and acceleration sensitivity

3.2.2.1.2 Short-period damping

Discussion

The requirements under 3.2.2 are concerned with the vehicle maneuvering characteristics in response to pilot inputs. These maneuvering responses occur over a relatively short period of time during which the flight conditions of the vehicle in terms of speed, altitude and dynamic pressure have not varied significantly from the dynamic response point of view. These conditions usually prevail for airplanes and are expected to prevail for lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds. They may not prevail generally for a lifting re-entry vehicle flying over all the Flight Phases of a fully operational lifting re-entry vehicle mission. The main topics of concern here are short-period responses, control feel during maneuvers, and pilot-induced oscillations.

Characteristics discussed such as short-period frequency, short-period damping, acceleration sensitivity, residual oscillations, control feel, control forces, and pilot-induced oscillations are the same characteristics specified for airplanes in MIL-F-8785B(ASG) and discussed in some detail in Reference 8. Some modifications to these requirements have been made to make them more applicable to lifting re-entry vehicles.

All indications are that the short-period frequency requirements of lifting re-entry vehicles should generally be similar to those of airplanes for a comparable Class. Any deficiencies in these requirements for airplanes are also likely to be deficiencies for lifting re-entry vehicles, although such generalizations can sometimes be misleading. The rationale and data presented in Reference 8 in support of short-period frequency requirements as a function of n/α apply equally well to lifting re-entry vehicles during terminal flight based on present experience with lifting re-entry vehicles.

Figure 1 in this specification indicates that short-period frequency requirements for all Flight Phase Categories of Class IV lifting re-entry vehicles are equal to the requirements for Category A Flight Phases for conventional airplanes. At low n/α 's, the Category C Flight Phase limits on n/α for lifting re-entry vehicles are identical to the Category C Flight Phase limits for Class IV airplanes. Flight experience with small lifting re-entry vehicles such as the M2-F2, HL-10, X-24A, and the X 15 airplane tend to substantiate the feeling that in their longitudinal requirements, Class IV lifting re-entry vehicles are most like Class IV airplanes, even though the rapid maneuverability and high load factors associated with Class IV airplanes are not generally applicable to Class IV lifting re-entry vehicles. Experience has indicated that precise flight-path control and reasonably rapid maneuvering may be important considerations for Class IV lifting re-entry vehicles during Category C Flight Phases. This is especially the case with unpowered vehicles in the landing approach. Flight experience also indicates that Class IV lifting re-entry vehicles are marginal in their lateral-directional characteristics, even when the vehicles are augmented, and the vehicles are generally more sensitive to turbulence than is the case for conventional airplanes. All of these factors combined to suggest that the lower boundaries of $\omega_{n_{sp}}^2 / (n/\alpha)$ for Class IV lifting re-entry vehicles in all Flight Phase Categories should be the same as the lower boundaries for Category A Flight Phases of airplanes. A Class IV lifting re-entry vehicle with sluggish response or inadequate sensitivity is likely to be significantly more difficult to fly than a Class IV airplane for the reasons presented. The upper boundaries on $\omega_{n_{sp}}^2 / (n/\alpha)$ are the same for all Flight Phase Categories of airplane and lifting re-entry vehicles to limit the degree of abruptness or high sensitivity of the response. There is no justifiable reason for changing these boundaries for lifting re-entry vehicles.

Lower limits on $\omega_{n_{sp}}$ are associated with tasks requiring precise control of pitch attitude, and lower limits on $\omega_{n_{sp}}$ and n/α are expected to be associated with precise control of attitude and flight-path angle, especially for Category C Flight Phases. Both $\omega_{n_{sp}}$ and n/α lower boundaries are subjects

for a great deal of discussion and difference of opinion which are difficult to resolve with the available data. Except for some qualifications on the lower limit requirements of $\omega_{n_{sp}}$ and n/α that will be discussed later, it seemed reasonable to keep the lower limits on $\omega_{n_{sp}}$ the same as Category A Flight Phases of airplanes and the lower limits on n/α the same as Category C Flight Phases of Class IV airplanes.

Class III lifting re-entry vehicles are most like Class III airplanes. No actual flight experience exists for Class III lifting re-entry vehicles. Until quite recently, due to NASA efforts in connection with the SSV, no Class III lifting re-entry vehicles have been given serious consideration. The short-period frequency requirements established for Class III lifting re-entry vehicles are shown as Figure 2 in the requirements presented in Section II. Category C lower boundaries of $\omega_{n_{sp}}^2/(n/\alpha)$ for lifting re-entry vehicles are the same as the Category C lower boundaries for airplanes. Category A and B lower boundaries are essentially the same as Category B lower boundaries for airplanes with one exception. In the interest of simplicity, the Level 1 lower boundary was raised slightly from $\omega_{n_{sp}}^2/(n/\alpha) = 0.085$ to $\omega_{n_{sp}}^2/(n/\alpha) = 0.096$ to coincide with the Level 2 and 3 boundary for Flight Phase Category C. The lower limits on $\omega_{n_{sp}}$ at low n/α 's and the lower limits on n/α for Category C Flight Phases are identical to those of Class III airplanes. Class III lifting re-entry vehicles, because of their weights and inertias, are expected to be less sensitive to turbulence effects than Class IV lifting re-entry vehicle. This, coupled with the lack of data and flight experience, appears not to justify any stricter requirements for Class III lifting re-entry vehicles.

Lower limits on $\omega_{n_{sp}}$ are associated with a degradation of the sensitivity of the vehicle, i.e., the response becomes sluggish and the attitude changes following a pilot input are slow and difficult to predict. Lower limits on n/α , or L_α , are associated with a decrease in the responsiveness of the vehicle in terms of flight-path angle changes. Adequate and sufficiently rapid flight-path angle changes are especially important in the landing approach Flight Phase. Lower limits on L_α and n/α are difficult to establish based on the available data, and to some extent these lower limits are arbitrary. It is also true that lower limits on n/α can impose design constraints on the maximum C_L of the vehicle or its wing loading, but constraints on C_L or wing loading are not likely to be a serious consideration for lifting re-entry vehicles, especially unpowered vehicles which are required to fly much or all of the approach and landing on the frontside of the $(L/D)_{\max}$ curve. In view of these considerations, it was decided that the n/α requirements can be relaxed if adequate justification can be presented to the procuring activity. As is the case for airplanes, both $\omega_{n_{sp}}$ and n/α requirements can be relaxed if suitable means are provided for controlling lift directly.

For the unpowered landing of Class III vehicles, there is some indication that the sluggish response will make it difficult to obtain adequate flight-path changes without overdriving the vehicle through the pitch control which can lead to closed-loop difficulties in flight-path control during the landing

approach. Therefore, the adequacy of the lower limit on ω_{nsp} for Class III vehicles must be established by the contractor for unpowered landings.

Considerable data are presented in Reference 8 from which these short-period frequency requirements were established for airplanes. Handling qualities data on short-period frequency requirements of lifting re-entry vehicles is extremely limited. Nothing in published reports appears to refute the requirements established here during terminal flight at low supersonic, transonic, or subsonic speeds. There are differences of opinion, based on limited and inconclusive data for airplanes, on the limits on ω_{nsp} at low n/α 's and the lower limits on n/α , especially for Category C Flight Phases. Some of these differences extend to what the important parameters are in this flight area and how the requirements should be stated in terms of these parameters.

Reference 35 presents some data on flight test results with the M2-F2 and HL-10 lifting re-entry vehicles, and some fixed-base ground simulator results based on a simulation of an HL-10 shuttle, i.e., an HL-10 increased in size to perform the Shuttle mission (Figures 12 and 13). Flight test results on the HL-10 and M2-F2 agree quite well with the specification requirements for Class IV vehicles. Also shown on Figure 12 are some flight test results of the X-24A obtained from unpublished data. The HL-10 shuttle ground simulator results (Figure 13) tend to show more restrictive boundaries on n/α for both Level 1 and Level 2. The Level 1 boundaries on frequency agree with the specification, but the Level 2 boundaries on frequency are expanded. The lack of proper proprioceptive pilot cues may be an important consideration in these discrepancies since it has been established that proper proprioceptive cues are important in establishing short-period frequency requirements. Many of the experimental details concerning these results are not known.

There is ample evidence in the published literature that the short period frequency requirements can usually be met, at least during subsonic terminal flight, and often without augmentation. Data on the M2-F2, HL-10, X-24A, X-15, and X-20 were examined. Very little definitive pilot rating or comment data exist to go with these short-period frequencies, so the data are not presented.

For an operational lifting re-entry vehicle, the short-period damping requirements follow essentially the airplane requirements in MIL-F-8785B(ASG) with one notable exception. Category A Flight Phases for lifting re-entry vehicles are certainly not as demanding as Category A Flight Phases of airplanes, and they are certainly not as demanding as Category C Flight Phases of airplanes or lifting re-entry vehicles. Based on the categorization of re-entry vehicle Flight Phases, Category A and B Flight Phases are now logically grouped together in specifying short-period damping requirements for re-entry vehicles.

The data upon which these damping requirements are based are presented in Reference 8, and these data actually indicate lower damping requirements than those specified. It was felt that although the data did include the effects of turbulence to some degree, the lower limits would not be adequate

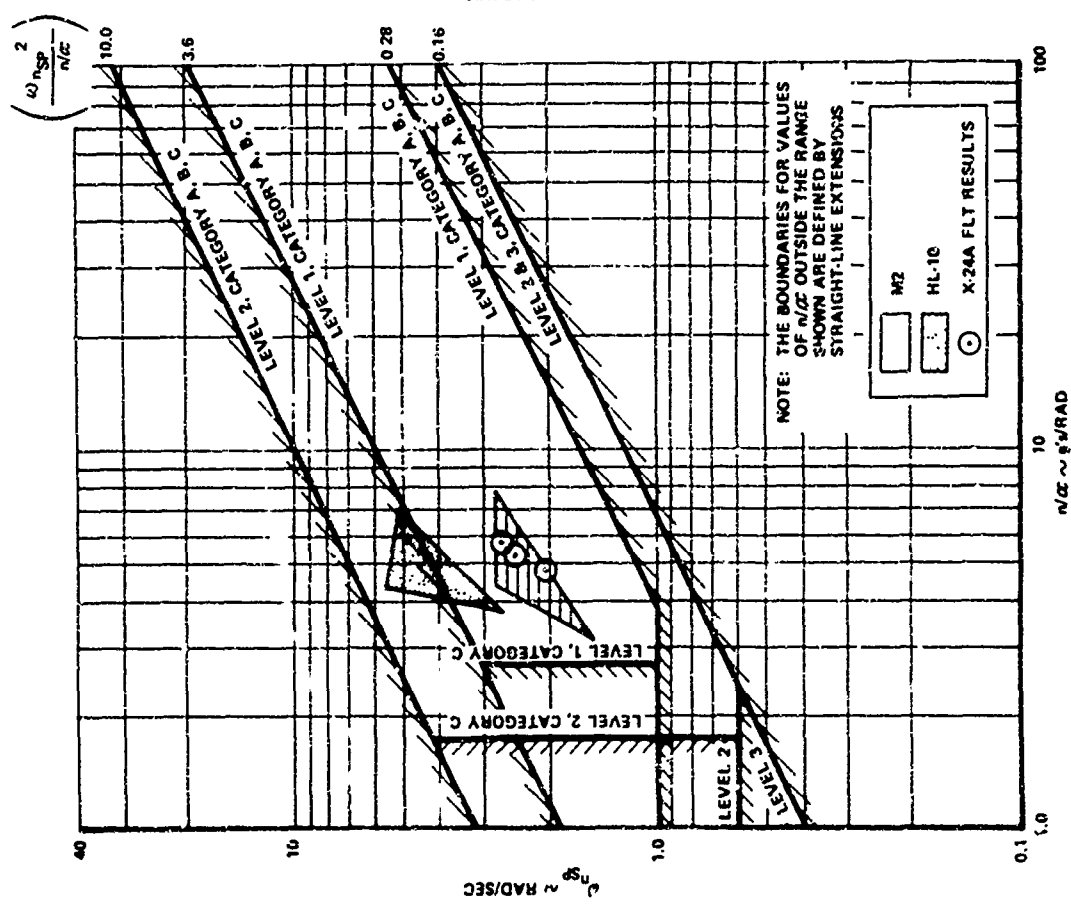


Figure 12 COMPARISON OF M2-F2, HL-10 AND X-24A FLIGHT TEST RESULTS TO CLASS IV SHORT-PERIOD FREQUENCY REQUIREMENTS

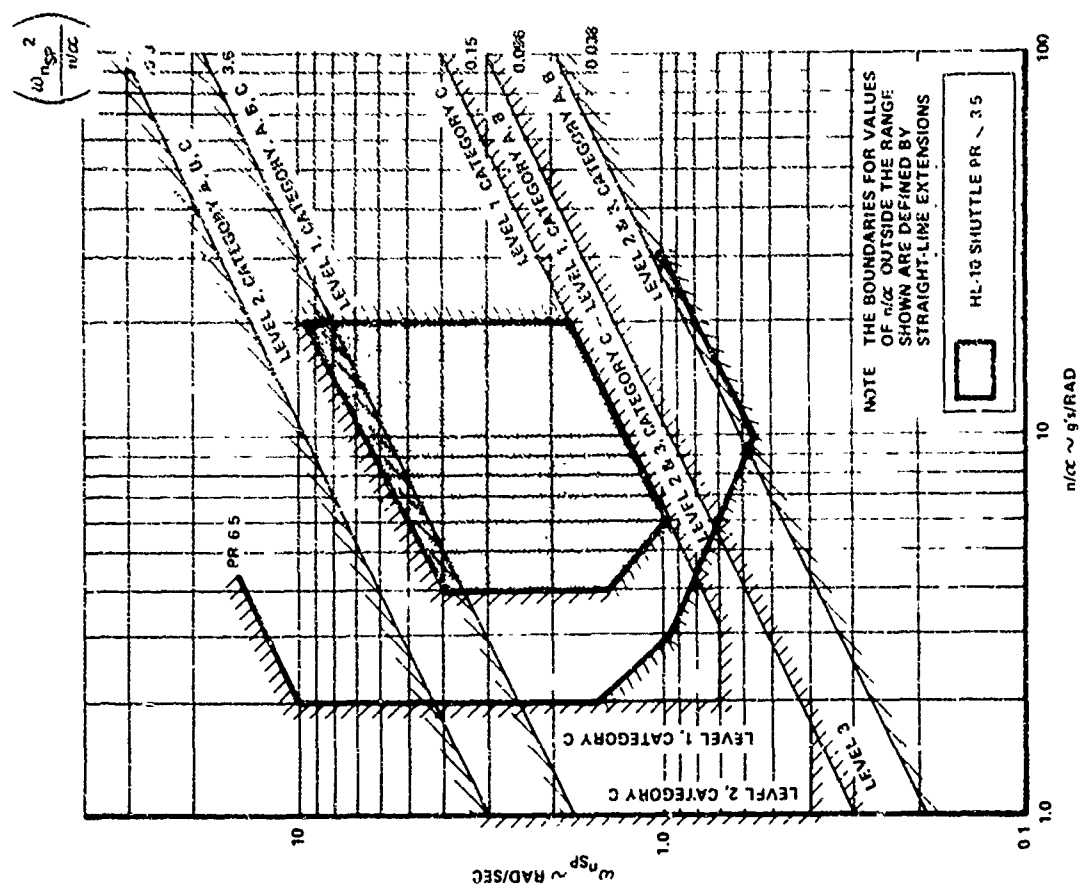


Figure 13 COMPARISON OF HL-10 SHUTTLE GROUND SIMULATION RESULTS TO CLASS III SHORT-PERIOD FREQUENCY REQUIREMENTS

under realistic turbulence conditions, therefore the lower limits were increased to those shown. Since experimental lifting re-entry vehicles are likely to operate under significantly lower turbulence levels than operational vehicles, it was felt that the minimum damping requirements indicated by the data and presented in Reference 8 should be adequate for experimental vehicles.

The upper limits of ζ_{sp} in MIL-F-8785B(ASG) are based mostly on engineering judgment, therefore it seemed advisable to allow the upper limits to be relaxed for lifting re-entry vehicles, at least for Category C Flight Phases, if such relaxation can be justified by the contractor and approval is obtained from the procuring activity.

A recent in-flight simulation program investigated minimum longitudinal handling qualities for transport aircraft (Reference 36). These flight test results were obtained by NASA Flight Research Center in their GPAS airplane. These results indicate that a transport airplane in cruising flight (Category B Flight Phase) can have more lenient requirements than those specified in both damping and frequency and still have acceptable handling qualities (Pilot Rating less than 6.5). In fact, with frequencies greater than 1.0 to 1.5, some negative damping is acceptable. The results also indicate that a degree of static instability is acceptable if the airplane has adequate damping. The tests were performed VFR in daylight and in smooth air. It would, however, be necessary to perform these same tests with turbulence before definite recommendations can be made to relax the damping requirements and the requirements on $\omega_{n_{sp}}^2 / (n/u)$.

Reference 37 presents some short-period frequency and damping ratio data, with associated pilot rating, on the X-15 airplane between $M = 2.5$ to 5.5 and $q = 100$ to 1400 pounds per square foot. The data are not presented here since no explanation of flight conditions and tasks associated with the ratings is presented in the report, except that the flight conditions were at high Mach numbers and must have been at reasonably high altitudes. It is assumed that these can probably be considered as Category A or B Flight Phases. All of the data presented agree quite well with the requirements established for a Class IV (E), i.e., a Class IV experimental vehicle.

Suggestions have been made, especially for Category C Flight Phases, that short-period requirements are more complex and are not adequately covered by the requirements as stated in MIL-F-8785B(ASG). Requirements on $\omega_{n_{sp}}$ and $2\zeta_{sp}\omega_{n_{sp}}$ as functions of $1/\tau_{\theta 2}$ or L_d have been suggested as well as requirements for minimum n/u as a function of airspeed (V_0). None of these requirements, based on existing data, is adequately supported or introduces any significant improvements over the requirements as they are presently stated. Additional experimental and theoretical work in this area is desirable to establish more definitive requirements.

Requirement

3.2.2.1.3 Residual oscillations

Discussion

This paragraph is essentially a qualitative requirement on residual oscillations as they reflect on the handling qualities of the vehicle. The requirement as stated for re-entry vehicles does emphasize the fact that residual oscillations due to limit cycle and structural resonance are to be considered with the flight control system SAS gains required to meet handling qualities requirements. Experience with the X-15, M2-F2, and X-24A vehicles has emphasized the fact that SAS systems can lead to limit cycle and structural resonance problems and these problems are a function of the gains required in the SAS system channels. The requirement on pitch-attitude oscillations less than ± 3 mils for Category A Flight Phases, which appears in MIL-F-8785B(ASC), has been removed since tight tracking, in-flight refueling, or formation flying are not requirements for Category A Flight Phases of re-entry vehicles.

In a preliminary draft of lifting re-entry vehicle handling qualities requirements (Reference 9), very specific quantitative requirements on limit cycle and structural resonance were presented and these were obtained from Reference 38. After considerable investigation of the data and discussions with personnel at NASA Edwards, it was decided that the requirements were in reality not handling qualities requirements but flight control system requirements. Therefore, these quantitative requirements have been removed; the rationale is presented below.

Limit cycles are self-sustaining oscillations in closed-loop systems caused by phase lag introduced through nonlinearities such as hysteresis, "slop", and "dead-band". Since all flight control systems exhibit electrical or mechanical nonlinearities, all augmented vehicles will have limit cycles to some degree. In lifting re-entry vehicles, where it may be desirable or necessary to operate at high augmentation system gains, there is a danger of limit cycles reaching magnitudes which might cause loss of control by the pilot or destruction of the vehicle. NASA FRC at Edwards, California has developed a ground testing technique for limit cycle characteristics which has been applied to aircraft such as the X-15, F-111, and to lifting bodies such as M2-F2, HL-10, and X-24A.

Figure 14 is a block diagram of a typical ground test setup. The analog computer is used to simulate the vehicle response to control surface motion. A single vehicle transfer function in the analog computer relates vehicle rate to control surface deflection. The computed angular rate operates the vehicle gyro through a torque circuit. The test technique consists of introducing a disturbance into the system through the pilot controls at each level of total loop gain to be tested. As an example, the total pitch loop gain is $K_q M_{\delta_e}$, SAS gain ($K_q = \delta_e / q$) times the control power M_{δ_e} . The elevator limit cycle amplitude, $K_q \Delta q$ (SAS gain times pitch rate peak to peak amplitude),

and limit cycle frequency are plotted as functions of total loop gain ($K_g M_{\delta_e}$) in Figure 15. Figure 15 was taken from Reference 38 and shows the limit cycle characteristics of the X-24A. Typically, as total loop gain is increased, both the limit cycle amplitude and frequency increase. At low gains, the limit cycle is primarily attributable to hysteresis effects in the control system. At higher gains, the phase lag due to hysteresis diminishes and phase lags due to elements such as the gyros and servo actuators begin to predominate. The knee in the limit cycle amplitude versus loop gain plot corresponds to the condition where the total loop phase lag begins to exceed 180 degrees. This condition is called the crossover point.

If the total loop gain continues to increase beyond the crossover point, the limit cycle becomes unstable. Further increases in gain can result in rate limits of the control surface actuators. Under these conditions, the control actuators cannot respond to stabilizing signals from the SAS and the oscillations will rapidly diverge. Depending on the control system configuration, rate limiting of control surface actuators cannot respond to stabilizing signals from the SAS and the oscillations will rapidly diverge. Depending on the control system configuration, rate limiting of control surface actuators may also result in forces being fed back to the pilot's controls.

Reference 38 states that flight test experience has shown that the amplitude of the steady-state control surface limit cycle is a good indication of both the proximity of the limit cycle to the crossover point and the degree of pilot concern about the magnitude of the limit cycle. Figure 16 from Reference 38 presents a limit cycle acceptance criteria in terms of limit cycle control surface amplitude. The various regions have been established through flight test experience with high performance aircraft and manned lifting bodies. A qualitative description of the vehicle characteristics appropriate to each of the regions from the pilot's point of view are summarized below as obtained from Reference 38.

- | | |
|---------------------|---|
| <u>Acceptable</u> | - Limit cycle unnoticed by the pilot in flight, causes no problems in controlling the vehicle |
| <u>Marginal</u> | - Limit cycles detected by the pilot, controllability decreased for precise maneuvers. The pilot feels the normal acceleration and sometimes may feel that it is buffet. It gives the pilot the feeling that he is going to lose control of the vehicle |
| <u>Unacceptable</u> | - Limit cycles can cause the pilot to lose control of the vehicle |
| <u>Destructive</u> | - Aerodynamic loads approach the structural limitations of the vehicle and continue until failure occurs |

Based on the above word descriptions, it may appear that limit cycle amplitudes in the acceptable region are a requirement for Level 1 handling

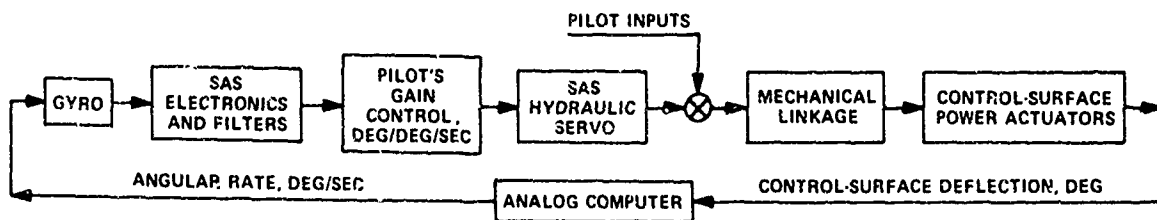


Figure 14 GROUND TEST SET-UP

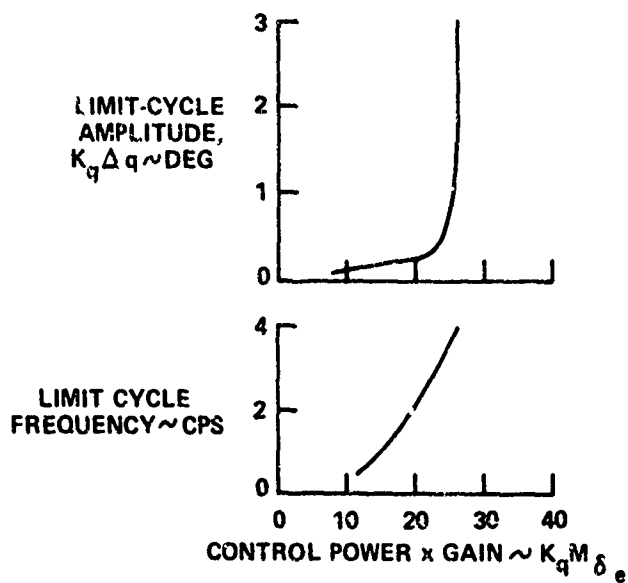


Figure 15 X-24A PITCH LIMIT-CYCLE CHARACTERISTICS

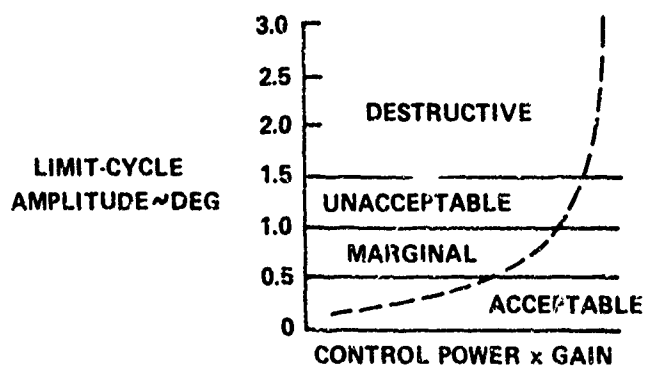


Figure 16 LIMIT CYCLE ACCEPTANCE CRITERIA

qualities. Similarly limit cycles in the Marginal and Unacceptable region might be considered as requirements for Level 2 and Level 3 handling qualities. This association of handling qualities regions with Levels was responsible for the preliminary limit cycle requirements presented in Reference 9.

On closer examination, it was decided that the regions and their word descriptions are probably not easily equatable to handling qualities and handling qualities Levels. It is obvious that the Acceptable limit cycle region would lead to no handling qualities problem and would certainly be in Level 1. The Marginal region indicates that limit cycles are "detected" by the pilot, but the pilot feels he is going to lose control of the vehicle. These two word descriptions seem inconsistent except for the qualifying words "the pilot feels". Also, how are these words related to an "increase in pilot workload or degradation in mission effectiveness or both", that would lead one to believe that this amplitude of limit cycle would result in Level 2 handling qualities? The description of the Unacceptable limit cycle region states that the "limit cycles can cause the pilot to lose control of the vehicle", yet with Level 3 handling qualities, safe control of the vehicle is never in doubt. It is also interesting to note that increasing the limit cycle amplitude that is just detectable (Marginal region) by less than 50 percent will lead to limit cycles that "can cause the pilot to lose control of the vehicle" (Unacceptable region).

It appears that the word descriptions of limit cycle levels are more associated with pilot anxiety than they are with handling qualities control problems, as such. If, in fact, the limit cycles are related to handling qualities, they must be so related by the oscillatory accelerations in the pilot's cockpit due to the limit cycles. This would suggest that a knowledge of the cockpit acceleration levels at each of the boundaries would allow a meaningful handling qualities criterion to be related to "g" levels at the pilot's station. Such g levels are a function of more than just control surface limit cycle amplitude and frequency. They are a function also of control surface effectiveness, vehicle dynamics at the limit cycle frequency, pilot's location with respect to the c.g., nonlinearities, etc. All of these characteristics would lead to different g levels in going from one vehicle to another even though the control surface limit cycle amplitude is the same. Since no published acceleration data were available, the cockpit normal acceleration levels at the limit cycle criteria boundaries were calculated for two of the lifting body configurations using a two-degree-of-freedom analysis.

For the original HL-10 SAS system, the limit cycle frequencies at the limit cycle boundaries were as follows:

<u>Region</u>	<u>$K_q \Delta q$ (Degrees peak to peak)</u>	<u>Frequency (cycles/second)</u>
Acceptable	0.5	1.8
Marginal	1.0	2.4
Unacceptable	1.5	2.6

If it is assumed that $\kappa_q \Delta q = \delta_e$, i.e., that there is negligible gain attenuation due to augmentation loop dynamics, it is possible to estimate the cockpit acceleration amplitude at the region boundaries. The results are as follows:

<u>Region</u>	<u>$\kappa_q \Delta q$ (Degrees peak to peak)</u>	<u>Cockpit Acceleration (g's)</u>
Acceptable	0.5	.006
Marginal	1.0	.012
Unacceptable	1.5	.020

Similar calculations for the M2-F2 yield the following acceleration levels

<u>Region</u>	<u>$\kappa_q \Delta q$ (Degrees peak to peak)</u>	<u>Cockpit Accelerations (g's)</u>
Acceptable	0.5	.001
Marginal	1.0	.003
Unacceptable	1.5	.006

Reference 39 indicates that over the frequency range associated with limit cycles, the acceleration perception threshold is of the order of 0.001 g's. Thus the acceleration levels estimated for these lifting bodies at $\kappa_q \Delta q = 0.5$ would probably be noticeable to the pilot, but it is difficult to reconcile that the word descriptions associated with the regions are really descriptive of handling qualities characteristics related to the g levels at the pilot's cockpit. A "g" level due to a limit cycle of .01 to .02 at the pilot's station can hardly "cause the pilot to lose control".

Informal conversations with NASA-FRC personnel who have been intimately concerned with limit cycle problems, including pilots, indicates that the primary concern has been the anxiety of the pilot and the danger that the augmentation gains would reach levels that would cause limit cycle instability. It was pointed out that the vehicle motions under the conditions of limit cycle as presented in Reference 38 were not of particular concern from the standpoint of handling qualities difficulties, provided limit cycle instability was avoided. Reference was made to recent studies (Reference 40) conducted by the Flight Research Center (FRC) of NASA regarding the effects of buffet intensity on handling qualities in precision tracking tasks. Although these aircraft motions under buffet conditions have a continuous power spectrum rather than a line spectrum as is the case with limit cycle motions, these experiments are of significance to the limit cycle question. The results indicate that buffet intensity variations between 0 to 0.2 g's rms produced very small changes in tracking precision for three high performance aircraft. However, tracking errors increased greatly when the handling qualities of the aircraft were

degraded by such factors as high adverse yaw. It is concluded that much higher acceleration levels can be tolerated with little loss of mission effectiveness than the levels computed at the limit cycle criteria boundaries of Reference 38. These criteria are more related to control system design requirements to prevent augmentation system gains from reaching levels which can drive the limit cycle unstable with the resulting danger of damage to the flight control system, or structural damage to the airplane.

Similar arguments are applicable to control system gains that will cause structural resonance, i.e., control system gains that cause structural resonance are to be avoided for reasons other than handling qualities, reasons such as structural damage due to fatigue, etc.

Requirements

3.2.2.2 Control feel and control motion in maneuvering flight

3.2.2.2.1 Control forces in maneuvering flight

3.2.2.2.2 Control motions in maneuvering flight

Discussion

The title of 3.2.2.2 has been changed from "Control feel and stability in maneuvering flight", which appears in MIL-F-8785B(ASG), to "Control feel and control motion in maneuvering flight". This emphasizes that the requirement has been changed such that a stable variation of elevator surface positions with normal acceleration is no longer required.

The requirement of stable control force and position variations with normal acceleration at constant speed will insure that the vehicle has a stick-free and stick-fixed short-period mode. The deletion of the requirement on stable control surface motions, and unaugmented vehicle static stability is thought to be justified for lifting re-entry vehicles that in all probability will be highly augmented. Reliability requirements for such vehicles and their subsystems will generally be high because of high program and vehicle costs, mission complexity, passenger safety, and vehicle and environmental unknowns. It is also true that in some instances, design requirements for optimizing payload will be very critical considerations, and allowing more aft c.g. positions, or unaugmented vehicle static instability for some Flight Phases may be an important consideration in the optimization process. All of these factors tend to suggest that once the handling qualities levels and reliability requirements are met, there should not be an inconsistent and special requirement that does not allow the basic, unaugmented vehicle to be unstable.

This is another instance where some data, such as that in Reference 36, indicate that some instability may be tolerated for Level 3 and possibly even Level 2. But concerns for such effects as turbulence, design uncertainties, and having several Level 3 flying qualities at the same time have resulted in the specification of more conservative requirements.

It should be emphasized that augmenting an unstable vehicle to a particular level of stability will imply a larger percentage of total control deflections or control power for augmentation than is true for a stable vehicle. In such cases, one must be assured that sufficient control power remains for maneuvering and trimming the vehicle during all of its Flight Phases.

The minimum and maximum maneuver force gradient limits (F_s/n) at the higher n/α 's are the same for lifting re-entry vehicles and airplanes as specified in MIL-F-8785B(ASG). As is true for airplanes, the gradients are higher for wheel controllers than for center-stick controllers. In the case of unpowered lifting re-entry vehicles, the requirements apply in steady gliding turns at constant indicated airspeed. Lifting re-entry vehicles in terminal flight fly and maneuver much like airplanes; it therefore appears to be rational to make the requirements a function of limit load factor as is the case for airplanes.

As explained in Reference 8, there is ample evidence that at very low values of n/α , F_s/n can and should be higher than at high values of n/α . Given a choice (References 41 and 42), the pilot tends to select a constant value of F_s/n at high n/α , but a constant value of F_s/α at low n/α . At low n/α the pilot is concerned with the control of pitch attitude. These factors are related by the following formula:

$$\frac{F_s}{n} = \frac{\frac{F_s}{\alpha}}{\frac{n}{\alpha}}$$

At low n/α 's, if F_s/α is held fixed at some desired value, then F_s/n will vary inversely with n/α . The requirements for airplanes in MIL-F-8785B(ASG) also specify fixed maximum and minimum values of F_s/n under certain conditions. For airplanes, as n/α decreases, F_s/α will decrease when F_s/n is held constant at its fixed maximum or minimum values.

Although there may be rational reasons for establishing upper limits on F_s/n at low values of n/α for airplanes, such upper limits are not well founded, and this is especially true for lifting re-entry vehicles which will fly under flight conditions of low dynamic pressure where n/α is small. Fixing the maximum value of F_s/n will imply that the same attitude changes of the vehicle can be made with lower stick forces as n/α is reduced. Whether such low values of F_s/α at low dynamic pressures are permissible or desirable is a function of many things such as mission, tasks, and the kind of stabilization system provided for the vehicle. Such requirements are outside the scope of this specification which is expected to apply only when the vehicle is in essentially atmospheric flight and it can develop aerodynamic forces to essentially sustain the weight of the vehicle.

It was decided that for the purposes of this specification the fixed upper limits on maximum F_s/n at low n/α 's would be eliminated for Level 1 and Level 2. This allows maximum F_s/n to vary inversely with n/α , and F_s/α to remain constant as n/α is reduced. For Level 3 the fixed upper limits for

maximum F_s/n are the same as the requirements for airplanes, except that Level 3 values of maximum F_s/n are not allowed to be lower than Level 2 values. The minimum limits on F_s/n were allowed to remain the same for lifting re-entry vehicles and airplanes. When F_s/n is fixed and independent of n/α , F_s/α is allowed to decrease as n/α decreases.

It is well to point out that the requirements for lifting re-entry vehicles differ from the requirements for airplanes only when n/α is less than 8.5 for center-stick controllers and less than 4.25 for wheel controllers.

The limited data available and presented in Reference 8 indicate that no requirements can be established for Category C Flight Phases on minimum elevator control force per inch of control deflection for airplanes. The limited data available for Category A Flight Phases appear to indicate that control force per inch of elevator-control deflection at constant speed should not be less than 17 pounds per inch for Level 1 and not less than 7 pounds per inch for Level 2. Contractors have objected to these large values and have cited numerous examples of airplanes and re-entry vehicles with smaller values that have been acceptable to pilots. Therefore a minimum value of 5 pounds per inch was specified for airplanes for Category A Flight Phases. In the case of lifting re-entry vehicles, this value is specified only for Category C Flight Phases since Category C for re-entry vehicles is most comparable to Category A for airplanes in terms of precision attitude and flight-path control.

Requirements

3.2.2.3 Longitudinal pilot-induced oscillations

3.2.2.3.1 Transient control forces

Discussion

The qualitative requirement on pilot-induced oscillations is the same requirement stated for airplanes in MIL-F-8785B(ASG). These requirements will of course be met with the SAS gains that are necessary to meet the other requirements of this specification. The requirement on PIO's is to be met whether the oscillations are caused by short-period dynamics, feel-system dynamics, control-system dynamics, friction, free play, hysteresis, bobweights, aeroelastic coupling, or any other characteristics or combinations of these factors for the complete vehicle.

It is hoped that eventually quantitative requirements can be established to eliminate PIO's, but the problem is not well enough understood at the present time. Reference 8 discusses in some detail the possible sources of PIO's in airplanes. The discussion is equally applicable to lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds. Some PIO-related factors discussed, such as bobweights, are not likely to be factors of importance to lifting re-entry vehicles. The discussion in Reference 8 should be referred to in order to obtain some insight into factors that should be considered if PIO tendencies are to be avoided in lifting re-entry vehicles.

Suggestions have been made for quantifying control system requirements to avoid or limit PIO tendencies. An analytic treatment of PIO tendencies is contained in Reference 44. A class of PIO's that can be related directly to control system phase lags has been investigated in flight and the results are presented in Reference 3. Some PIO tendencies that can be related to high short-period frequencies and low short-period damping were investigated experimentally in Reference 44. The effects of control system nonlinearities and pitch and normal acceleration bobweights are presented in Reference 5. Reference 4, a very recent in-flight research program, investigated some additional aspects of control system dynamics and contains information on their possible relationship to PIO's.

Based on the results of References 3, 5, and 44, it has been suggested that it should be possible to subdivide the combined dynamic effects of the control system and airframe into an "effective control system" and an "effective airframe". The "effective" control system phase lag can then be computed at the "effective" short-period frequency. An "effective" PIO parameter that relates PIO tendencies can then be computed as follows:

$$\sigma_{a_{eff}} = \frac{1}{2} \left(\frac{1}{\tau_{\theta_2}} - 2\zeta'_{sp} \omega'_{n_{sp}} \right)$$

The two-parameter effective control system phase lag and $\sigma_{a_{eff}}$ can be used to correlate the data of References 3, 5, and 44 to establish limits on control system and short-period dynamics to limit PIO tendencies for various handling qualities levels. Although some reasonable correlation of the data is possible based on these parameters, the same correlation is not possible when other data, such as the more recent data of Reference 4 is used. It appears that the difficulties are associated with the partitioning process into "effective" control system and "effective" airframe and how this is to be determined for complex control system transfer functions with poles and zeros in the vicinity of the poles and zeros of the airplane short period.

The requirement in Paragraph 3.2.2.3.1 is identical to the requirement in Paragraph 3.2.2.3.1 of MIL-F-8785B(ASG), and is equally applicable to lifting re-entry vehicles. The requirement will increase F_s/n for low values of ζ_{sp} (stick-free) and tend to inhibit PIO tendencies associated with low short-period damping.

Requirements

3.2.3 Longitudinal control

3.2.3.1 Longitudinal control in unaccelerated flight

3.2.3.2 Longitudinal control in maneuvering flight

Discussion

The requirements of the subparagraphs under 3.2.3 insure that the vehicle has adequate control effectiveness and the control forces required to perform certain specific maneuvers are within the capabilities of the pilot. The control effectiveness must be sufficient to attain certain load factors at any speed and altitude within the permissible envelope, and the effectiveness must be adequate for takeoffs, landings, dives, and sideslips. With some slight modifications, the requirements for airplanes which appear in MIL-F-8785B(ASG) are applicable to lifting re-entry vehicles.

Paragraph 3.2.3.3.1 is an addition to this lifting re-entry specification and covers longitudinal control requirements for air launched lifting re-entry vehicles. The X-15, M2-F2, HL-10, and X-24A are examples of experimental lifting re-entry vehicles which have been air launched. Paragraph 3.2.3.4.2 is an additional paragraph and covers special requirements associated with the landing of unpowered lifting re-entry vehicles, especially vehicles with a low $(L/D)_{\max}$. Included are special minimum requirements on the landing flare and float. Paragraph 3.2.3.4.3 covers the effects of adverse elevator lift and longitudinal flight-path control during landing. Although this requirement is applicable to large conventional airplanes, it is especially applicable to the unpowered landings of lifting re-entry vehicles.

The requirement on longitudinal control in MIL-F-8785B(ASG) for unaccelerated flight, Paragraph 3.2.3.1, is applicable to lifting re-entry vehicles with some modification. The requirement is applied to the Service Flight Envelope and it is therefore consistent with the essential airplane requirement. The minimum speed is therefore limited to the minimum service speed and not the stall speed as specified in MIL-F-8785B(ASG). This speed is undoubtedly more meaningful and realistic for a lifting re-entry vehicle. The requirement also applies to unpowered lifting re-entry vehicles during equilibrium glide flight.

The longitudinal control requirements for maneuvering flight of lifting re-entry vehicles are essentially the same as those for airplanes as they are presented in MIL-F-8785B(ASG). By applying the requirements to the Operational Flight Envelope of lifting re-entry vehicles generally, one avoids the numerical g requirements in MIL-F-8785B(ASG) which are associated with Level 3 and may not be very meaningful for lifting re-entry vehicles. Thus, for Level 1, operational load factors must be attainable within the operational Flight Envelope and these can vary with speed and altitude. Level 3 load factor requirements will be established by mutual agreement between the contractor and the procuring activity.

Requirements

3.2.3.3 Longitudinal control in takeoff

3.2.3.3.1 Longitudinal control during air launch

3.2.3.3.2 Longitudinal control force and travel in takeoff and during air launch

3.2.3.4 Longitudinal control in landing

3.2.3.4.1 Longitudinal control forces in landing

Discussion

The longitudinal control requirements in takeoff are similar to the requirements for airplanes that appear in MIL-F-8785B(ASG). One might suspect that such takeoff requirements are not applicable to lifting re-entry vehicles since most of the design concepts for lifting re-entry vehicles are based either on air launch of small experimental vehicles or the vertical launch of multi-staged and boosted lifting re-entry vehicles. The requirements for boosted vertical takeoff are not considered in this specification. A few lifting re-entry vehicle design concepts, such as those discussed in Reference 45, have considered horizontal takeoff lifting re-entry vehicles. It is also expected that vertically launched lifting re-entry vehicles, such as the two-stage Space Shuttle Booster and Orbiter, will be first flight tested as independent vehicles with horizontal takeoff. Thus these horizontal takeoff requirements are expected to apply to such vehicles.

The longitudinal control requirements for tail-wheel vehicles and operation from unprepared fields, which appear in MIL-F-8785B(ASG), were not adopted since these requirements are not considered to be applicable to lifting re-entry vehicles.

Paragraph 3.2.3.3.1 is titled "Longitudinal control in catapult takeoff" in MIL-F-8785B(ASG) and such requirements are not considered applicable to lifting re-entry vehicles. Air launched lifting re-entry vehicles, such as experimental vehicles like the X-15, M2-F2, HL-10, and X-24A, do have longitudinal control requirements during air launch and this paragraph is now concerned with these requirements.

Longitudinal and lateral-directional control requirements during air launch can be of considerable concern when the launched re-entry vehicle is required to traverse a changing air flow field as influenced by the launch vehicle. Proper trim at launch, adequate separation, and control requirements are often established through wind-tunnel testing.

Attempts were made in a previous version of a lifting re-entry vehicle handling qualities specification (Reference 9) to quantify some of the launch requirements. After a discussion with personnel at Edwards Air Force Base,

it was decided that, based on launch experience and the data available, it is not possible to establish quantitative launch requirements at this time. Launch requirements such as elevator effectiveness, dynamic transient motions, separation, and required normal accelerations have therefore been qualitatively specified.

The longitudinal control force and travel in takeoff for lifting re-entry vehicles are the same as the requirements for airplanes as they are presented in MIL-F-8785B(ASG). The requirements for Class IV-L airplanes are the same as Class IV lifting re-entry vehicles. The same is true of Class III airplanes and Class III lifting re-entry vehicles.

These same longitudinal control force and travel requirements are applied to lifting re-entry vehicles during air launch and takeoff since they appeared appropriate to both and no better basis for establishing launch requirements is available at present.

The longitudinal control requirements in landing for powered lifting re-entry vehicles are considered to be the same as the requirements in MIL-F-8785B(ASG) for airplanes. Nothing at the present time indicates that these requirements should be different.

For the landing of unpowered lifting re-entry vehicles, an additional requirement has been added that elevator control shall be sufficiently effective in landing, down to touchdown speed, such that an incremental 0.5 g's or more is available to the pilot without exceeding stall or the geometric limited touchdown attitude. An examination of X-15 landing data (Reference 30) for the first 30 unpowered flights of the X-15 indicates an average for the peak incremental g's (Δg) of 0.71 during the flare. The average incremental g's pulled during a flare are however much lower, of the order of 0.24. In discussion with Edwards personnel intimately concerned with flying lifting re-entry vehicles such as the X-15, M2-F2, HL-10, and X-24A in unpowered landings, an incremental (Δg) of 0.5 was thought to be a requirement down to minimum touchdown velocity. Such an increment is not inconsistent with the X-15 landing experience and it is therefore used.

The longitudinal control forces in landing which are appropriate for Class IV and Class III airplanes and appear in MIL-F-8785B(ASG) appear equally appropriate for Class IV and Class III lifting re-entry vehicles, respectively.

In landing low $(L/D)_{\max}$ lifting re-entry vehicles without power, it has been flight test experience to deploy the landing gear near the end of the flare and even at the beginning of the float period. Flaps when they are available are usually deflected during the flare or float. It is essential not to increase drag and sink rate and dissipate excess kinetic energy during the flare. The excess energy is required to give sufficient float time for crucial flight-path and attitude corrections prior to touchdown. The magnitude of any trim changes due to the deployment of any devices during the flare and float must be small in recognition of the demanding piloting task during this final critical

phase of flight. It appears that the pilot should not be confronted with larger trim changes than those specified in 3.2.3.4.1 with the vehicle close to the ground when the pilot is busy making final changes to the vehicle position and attitude just before landing.

Requirement

3.2.3.4.2 Power-off and unpowered longitudinal control requirements in landing

Discussion

This is a new requirement associated primarily with the power-off landing or the landing of unpowered vehicles with low $(L/D)_{\max}$'s. Unpowered landing techniques upon which these requirements are based were developed by NASA Flight Research Center (FRC) and the Air Force Flight Test Center (AFFTC) at Edwards Air Force Base in California. These techniques evolved over a number of years through the use of experimental aircraft and became especially important and crucial to the dead-stick landing of lifting re-entry configurations such as the M2-F2 with an $(L/D)_{\max}$ of approximately 3.0. There is increasing evidence that these techniques are also applicable to unpowered landings of larger vehicles (Reference 46) and that the techniques are applicable to unpowered landings of larger vehicles (Reference 46) and that the techniques are applicable to operational as well as experimental vehicles.

Important aspects of the successful unpowered landing of lifting re-entry vehicles are good terminal area guidance, navigation, and energy management. But these problems impinge on handling qualities only to the extent that the pilot must be supplied adequate information for terminal area maneuvering and landing. The requirements specified here are only those associated with the terminal area preflare equilibrium glide, and flare, and the float to touchdown when the pilot is actively controlling the vehicle in a closed-loop sense to touchdown. Since the requirements presented are new, they are developed and discussed in some detail.

Unpowered landings of experimental vehicles have been made by NASA-FRC and AFFTC pilots at Edwards for over 20 years. Some of the first vehicles to land routinely without power were the X-1 and D-558-II. The subsonic $(L/D)_{\max}$'s of the X-1 and D-558-II are approximately 5.5 and 6.0 respectively. As the $(L/D)_{\max}$ decreased below 5.0, unpowered landings became a more critical piloting task. The X-15 has an $(L/D)_{\max}$ of approximately 4.2 clean and 3.4 with landing gear and flaps down. As stated in Reference 29:

"The terminal approach and landing techniques used for the X-15 have been highly successful. Although the landings are relatively routine, they do require exacting pilot performance and a high degree of proficiency. --- The cockpit window configuration and general external visibility are considered quite important in the performance of low L/D landings. The visibility from

the X-15 cockpit is considered excellent. The handling qualities of the X-15 in this speed and angle-of-attack range are also considered excellent. The all-movable horizontal tail for both pitch and roll control produces high airplane response with very little cross-coupling. All stability derivatives are stable and of fairly high magnitude in this flight regime. --- An effective method of speed control is necessary to perform accurate landings. The X-15's speed brakes have proven to be quite valuable during the approach and landing phase."

The $(L/D)_{\max}$ of the HL-10 in its landing configuration with the original tip fins is approximately 3.4. With the modified tip fins, this increases to approximately 4.0. The $(L/D)_{\max}$ s of the M2-F2 and X-24A are respectively 3.2 and 4.0 for the subsonic flight configurations flown at Edwards. None of these configurations have wings or landing flaps as such. The $(L/D)_{\max}$ with gear down for these vehicles is even lower. The gear is usually extended after flare completion during the float. In Reference 31, Gentry has made the following comment on M2-F2 landings:

"Another limitation of the M-2 was the steep flight path angle required on the approach to accomplish an unpowered flare and landing ----- Even under ideal flight conditions, I cannot imagine astronauts willing or proficient enough, after a space flight of any duration, to maneuver into a position to then dive at the ground with a vertical velocity of 15-18,000 feet per minute until they are only 1,000 feet above ground level. At that time they would initiate approximately a 2 "g" flare and have roughly 25 seconds to extend the landing gear and get the vehicle on the ground. There would be no go-around capability. I do consider this a reasonable task for our research program as we have had considerable F-104 and simulator practice. In addition, all our flights have been accomplished under controlled conditions in a familiar area and only on relatively calm VFR days."

Some modified F-104 landing studies are presented in Reference 47. Values of $(L/D)_{\max}$ down to 2.2 to 2.5 were simulated. As quoted from the conclusions of Reference 48:

"The pilots believed that the tolerable limit was reached with this airplane in the present configuration and that additional aids would be required to determine the flare-initiation point if, because of a further reduction in lift-drag ratio, more severe approaches than those experienced in this program were attempted."

High energy unpowered landing techniques that have been developed (Figure 17) attempt to keep the $(L/D)_{\max}$ as high as possible during the flare and still have sufficient time from flare completion to touchdown. The preflare approach is not made at a speed for $(L/D)_{\max}$, i.e., a speed for

minimum flight path angle, nor is it made at a speed for minimum sink rate, which is a speed lower than the speed for $(L/D)_{\max}$. The preflare equilibrium approach speed is a speed higher than the speed for $(L/D)_{\max}$ (Figure 18), so the approach is performed on the front side of the L/D curve. The flare is initiated by pulling normal g 's and the flare is completed very close to the C_L for $(L/D)_{\max}$. The pilot stops pulling g 's and the lift coefficient decreases and the vehicle flies on the front side again while floating parallel to the ground. The gear is lowered and if the vehicle has flaps they are also lowered and the vehicle continued to float on the front side of the L/D curve with gear and flaps down. The speed decreases and the lift coefficient increases until touchdown occurs at the speed for $(L/D)_{\max}$ with gear and flaps down.

It becomes readily apparent that for any given vehicle with a given $(L/D)_{\max}$, there are many kinds of different flares and floats that can be performed even though it is specified that the flare is to be completed at $(L/D)_{\max}$ and the touchdown is to be completed at $(L/D)_{\max}$. The variables in the problem are approach speed, flare initiation altitude, load factor during the flare, float time or runway distance, wing loading, etc.

The simplest way to treat the problem analytically is to work backwards from the touchdown conditions. The touchdown velocity is determined by C_L for $(L/D)_{\max}$ at touchdown and the vehicle wing loading. Integrating backwards, the float distance, float time, and float initiation velocity can be determined. These are a function of how far on the front side of the L/D curve the float was initiated, i.e., the value of $C_L/C_L(L/D)_{\max}$ with flaps and gear down, and when the flaps and/or the landing gear were lowered. This value of $C_L/C_L(L/D)_{\max}$ must also be compatible with the C_L for $(L/D)_{\max}$ while the vehicle is pulling g 's at the end of the flare with the flaps and/or the gear up. If the normal g 's are specified during the flare, either constant g 's or a time history of g 's, then it is possible to integrate the flare back to preflare equilibrium glide conditions and obtain the flare initiation altitude and velocity. This analysis can be repeated for the same vehicle making different assumptions along the way and a new flare and float trajectory can be determined with different initial conditions at flare initiation in terms of altitude, velocity, and flight-path angle. If one accepts "backside" operation during the flare and float, then the possible variables in the problem are increased further. Unpowered landings of vehicles with various (L/D) 's, wing loadings, and a variety of other assumptions have been documented and analyzed, such as in References 48, 49, and 33.

If $(L/D)_{\max}$ of a given vehicle is the only factor of importance in determining whether the vehicle is satisfactorily flared and landed, then all the flares and landings that can be computed analytically within the limitations of the vehicle must be thought of as satisfactory flares when performed by the pilot. But this hardly seems a reasonable conclusion. What is probably closer to the truth is that for a vehicle with a given $(L/D)_{\max}$ and wing loading, such as those of the X-15, there is a family of flares and landings that the vehicle can perform that are considered reasonably satisfactory by the pilot.

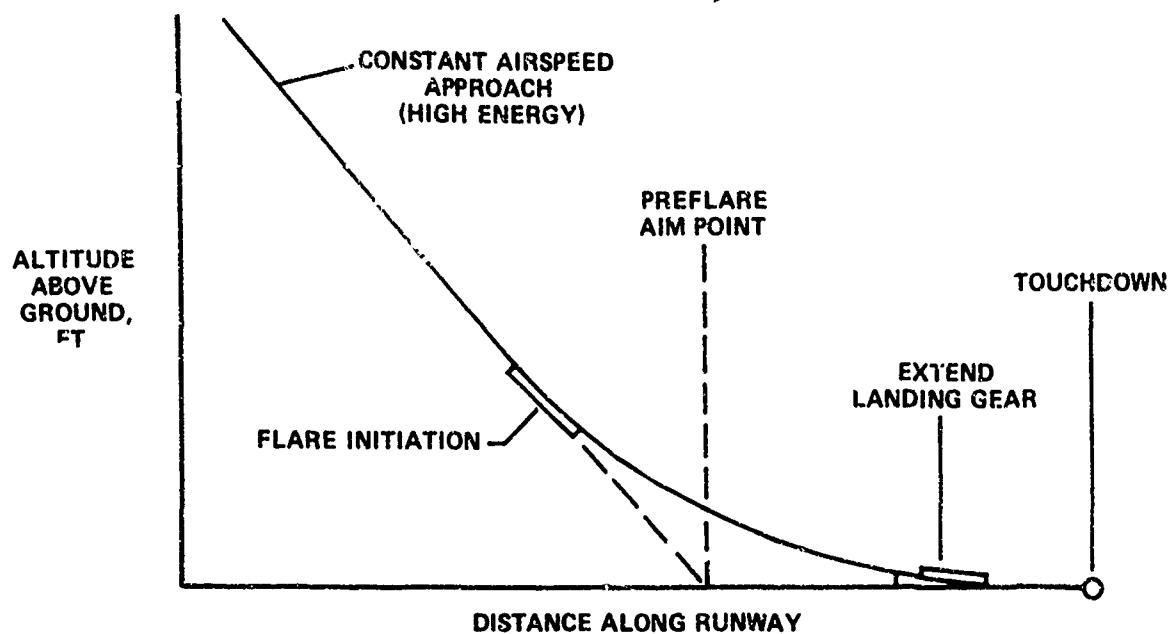


Figure 17 UNPOWERED FLARE AND LANDING PROFILE (REFERENCE 34)

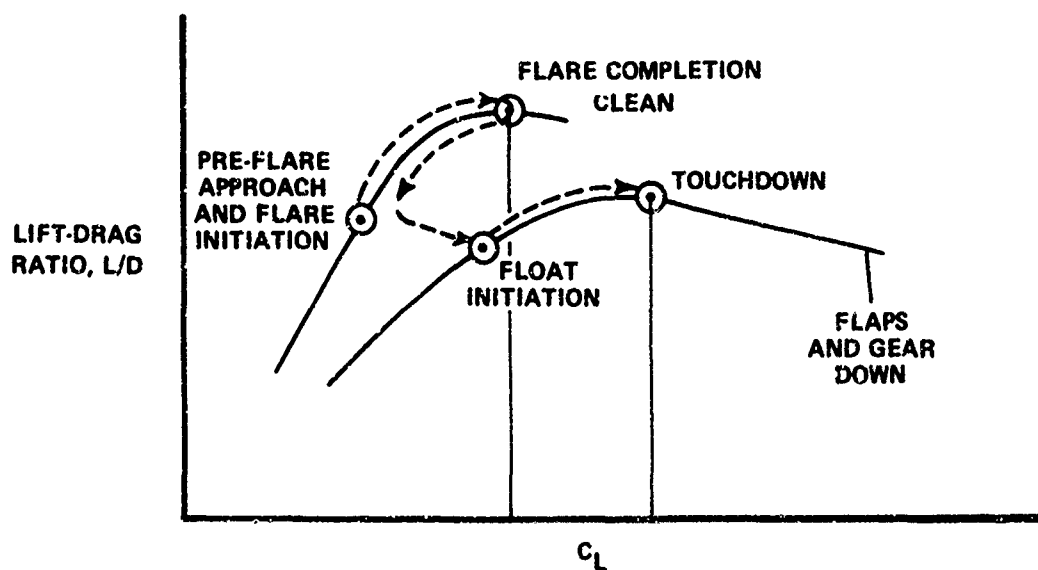


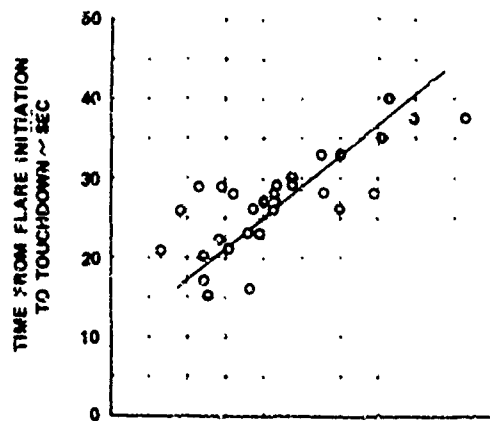
Figure 18 UNPOWERED LANDINGS C_L AND (L/D) RELATIONSHIPS (REFERENCE 29)

Outside this family, the flares of this vehicle will be unsatisfactory to a more or less degree and for various reasons. As the $(L/D)_{\max}$ of the vehicle increases, this family increases. As the $(L/D)_{\max}$ of the vehicle decreases, this family decreases in size until for a sufficiently low $(L/D)_{\max}$, let us say an $(L/D)_{\max} \approx 2.5$, none of the flares that can be performed analytically are acceptable when performed by a pilot in a closed-loop landing situation in the presence of the real physical environment.

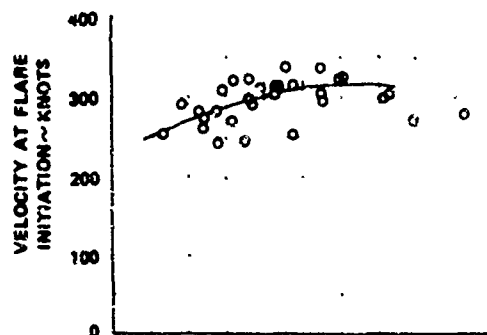
To explore these factors further it may be revealing to examine the published data of X-15 landings during the first 30 flights (Reference 30). Plots of these data are shown as Figures 19 and 20. Figure 19a indicates that the landings as flown by the X-15 pilots demonstrate an increase in time to touchdown from flare initiation altitude as the flare initiation altitude increases, but a reasonable amount of scatter exists in the data to indicate that the functional relationship is certainly not well established. Figure 19b is a plot of flare initiation velocity versus flare initiation altitude. Again there appears to be a trend of decreasing velocity with decreasing altitude but the scatter in the data is quite significant. Figure 19c is a plot of average acceleration normal to the flight path during the flare. The average normal accelerations are not contained in the data of Reference 30, but they were computed from the average velocity and flight path angle change during the flare. In spite of the scatter, a trend does exist that the higher the flare initiation altitude the lower the average normal acceleration in the flare. Figure 20a shows a definite trend of lower sink rate with lower flare initiation altitude and Figure 20b shows a trend of lower flight-path angle with lower flare initiation altitude.

What the data of Reference 30 indicate is that 30 successful unpowered landings of the X-15 were made by 7 pilots with flare initiation altitudes of 1850 feet down to 250 feet. The trends of the data indicate that as the flare initiation altitude decreases, the time to touchdown decreases, the flare initiation velocity decreases, the average normal acceleration during the flare increases, the sink rate at flare initiation decreases, and the flight-path angle decreases. It is also true that a significant amount of scatter exists about the trend lines faired through the data.

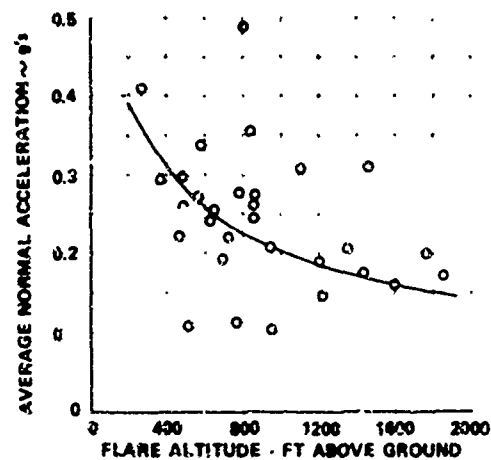
Unfortunately, no pilot rating or comment data exist for these 30 X-15 landings to indicate how the pilots liked each of the flares and floats to touchdown. The flares in the area near the trend lines, that do not include the extremes of flare altitude, are probably considered satisfactory by the pilots. As the flares deviate from this area, one would expect the flares to be at least less satisfactory to the pilot from the standpoint of workload, flare precision, etc. It is also probably true that some of the flares which are not in the satisfactory region are unsatisfactory because of the float to touchdown after the flare. It must be emphasized that these are conjectures that, although reasonable, are not supported by factual comment or rating data. It seems reasonable to conclude that a large variety or family of X-15 flares and landings are probably equally acceptable to the pilots, and a pilot with experience is likely to choose any of this family depending on the particular conditions of the landing.



a) FLARE ALTITUDE AND FLARE TIME

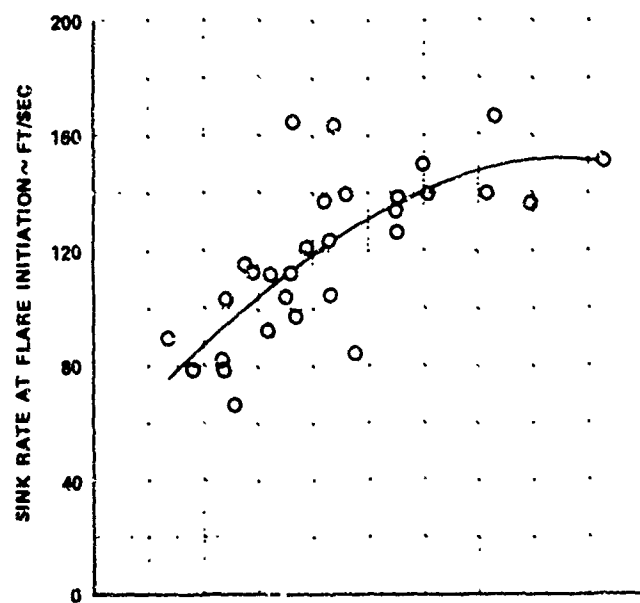


b) FLARE ALTITUDE AND FLARE VELOCITY

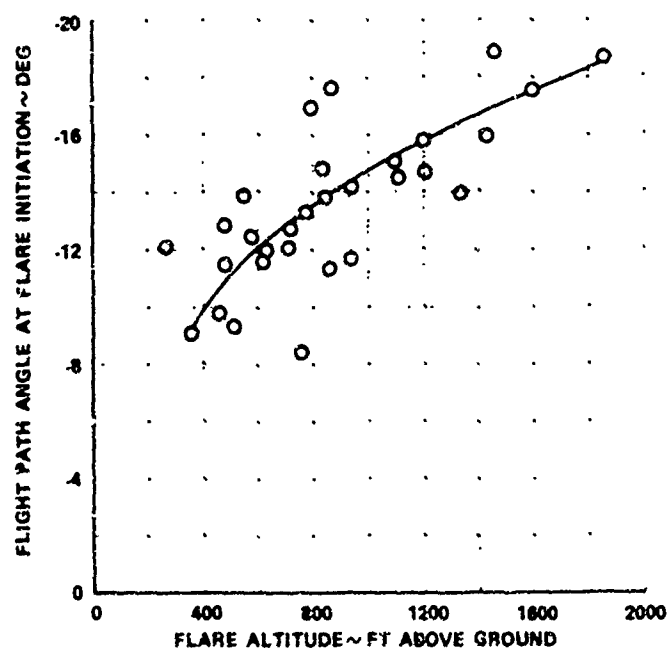


c) FLARE ALTITUDE AND NORMAL ACCELERATION

Figure 19 LANDING DATA ON FIRST 30 FLIGHTS OF X-15 (REFERENCE 30)



a) FLARE ALTITUDE AND SINK RATE



b) FLARE ALTITUDE AND FLIGHT PATH ANGLE

Figure 20 LANDING FLIGHT PATH DATA ON FIRST 30 FLIGHTS OF X-15 (REFERENCE 30)

When one considers all the factors that can contribute to the unpowered flare and float trajectory, and the variety of trajectories possible for a given lifting re-entry vehicle, one is at a loss to know how these parameters relate to one another to establish those particular flare and float trajectories that a pilot can and will fly and that will be considered acceptable to varying degrees in terms of Levels of handling qualities. A simple analytical examination of the flare and float phases, treated separately, will shed some light on this problem. The simplified analytical approach presented is a modification of that which appears in Reference 49.

The point-mass longitudinal trajectory equations of motion for an unpowered lifting re-entry vehicle can be written as follows:

$$\begin{aligned}\frac{W}{g} \dot{V} &= -D - W \sin \theta \\ \frac{W}{g} V \dot{\theta} &= L - W \cos \theta\end{aligned}\tag{9}$$

The rate of sink or altitude change with time and the rate of horizontal displacement of the vehicle become

$$\begin{aligned}\frac{dh}{dt} &= V \sin \theta \\ \frac{dx}{dt} &= V \cos \theta\end{aligned}\tag{10}$$

A differential element of time (dt) can be expressed as

$$dt = \frac{d\theta}{\dot{\theta}} = \frac{c'V}{\dot{V}}\tag{11}$$

Analysis of the Flare

Based on the above equations, it is possible to establish the following differential equations during the flare for t , h , and x in terms of flight-path angle and velocity

$$\begin{aligned}dt &= \frac{d\theta}{\dot{\theta}} \\ dh &= (V \sin \theta) dt = \frac{V \sin \theta}{\dot{\theta}} d\theta \\ dx &= (V \cos \theta) dt = \frac{V \cos \theta}{\dot{\theta}} d\theta\end{aligned}\tag{12}$$

The acceleration normal to the flight path in g's (n_g) becomes from the second of Equations (9)

$$\begin{aligned}\frac{V\dot{\gamma}}{g} &= n_g = \frac{L}{W} - \cos \gamma \\ \dot{\gamma} &= \frac{g}{V} n_g = \frac{g}{V} \left(\frac{L}{W} - \cos \gamma \right)\end{aligned}\quad (13)$$

Substituting Equation (13) into Equations (12) results in the following:

$$\begin{aligned}dt &= \frac{V}{g n_g} d\gamma = \frac{V d\gamma}{g \left(\frac{L}{W} - \cos \gamma \right)} \\ dh &= \frac{V^2 \sin \gamma}{g n_g} d\gamma = \frac{V^2 (\sin \gamma) d\gamma}{g \left(\frac{L}{W} - \cos \gamma \right)} \\ dx &= \frac{V^2 \cos \gamma}{g n_g} d\gamma = \frac{V^2 (\cos \gamma) d\gamma}{g \left(\frac{L}{W} - \cos \gamma \right)}\end{aligned}\quad (14)$$

If it is assumed for the purposes of this analysis that the normal acceleration is held reasonably constant during the flare, then

$$n_g = \frac{L}{W} - \cos \gamma = \text{constant}$$

It will be further assumed that the velocity change during the flare is not too large, and Equations (14) can be integrated assuming V and V^2 are constants and equal to their average values during the flare, i.e., the average of the values at the beginning and the end of the flare, so that:

$$(V_{AV})_f \approx \frac{1}{2} (V_{f_i} + V_{f_c}) = \text{constant}\quad (15)$$

$$(V_{AV})_f^2 \approx \frac{1}{2} (V_{f_i}^2 + V_{f_c}^2) \approx \frac{1}{4} (V_{f_i} + V_{f_c})^2 = \text{constant}$$

where

$(V_{AV})_f$ = average velocity during the flare

$(V_{AV})_f^2$ = average velocity squared during the flare

V_{f_i} = velocity at flare initiation

V_f = velocity at flare completion

Substituting V_{AV} and V_{AV}^2 for V and V^2 in Equations (14) and performing the integrations, we have:

$$\begin{aligned} t_f &= \int dt \approx \frac{(V_{AV})_f}{g n_g} \int_{\gamma_{f_i}}^{\gamma_{f_c}} d\gamma = \frac{(V_{AV})_f (\gamma_{f_c} - \gamma_{f_i})}{g n_g} \\ h_f &= \int dh \approx \frac{(V_{AV})_f^2}{g n_g} \int_{\gamma_{f_i}}^{\gamma_{f_c}} (\sin \gamma) d\gamma = - \frac{(V_{AV})_f^2}{g n_g} (\cos \gamma_{f_c} - \cos \gamma_{f_i}) \quad (15) \\ x_f &= \int dx \approx \frac{(V_{AV})_f^2}{g n_g} \int_{\gamma_{f_i}}^{\gamma_{f_c}} (\cos \gamma) d\gamma = \frac{(V_{AV})_f^2}{g n_g} (\sin \gamma_{f_c} - \sin \gamma_{f_i}) \end{aligned}$$

where

t_f = flare time

h_f = altitude change during flare

x_f = flare horizontal distance

$(V_{AV})_f$ = average flare velocity

γ_{f_i} = initial flare flight path angle or equilibrium glide angle at flare initiation

γ_{f_c} = flight path angle at completion of flare

It is now possible to ratio the three flare parameters (t_f , h_f , x_f) as follows:

$$\begin{aligned} \frac{h_f}{t_f} &\approx - (V_{AV})_f \frac{\cos \gamma_{f_c} - \cos \gamma_{f_i}}{\gamma_{f_c} - \gamma_{f_i}} \\ \frac{h_f}{x_f} &\approx - \frac{\cos \gamma_{f_c} - \cos \gamma_{f_i}}{\sin \gamma_{f_c} - \sin \gamma_{f_i}} \end{aligned} \quad (17)$$

$$\frac{x_f}{t_f} \approx (V_{AV})_f \frac{\sin \gamma_{fc} - \sin \gamma_{fi}}{\gamma_{fc} - \gamma_{fi}}$$

It is interesting to note that the first ratio of parameters is equivalent to an average rate of sink, the second is equivalent to an average flight path angle, and the third is equivalent to an average horizontal velocity during the flare. It will be further assumed that the flight-path angles are sufficiently small so that the following approximations are valid:

$$\cos \gamma_{fc} = 1 - \frac{1}{2} (\gamma_{fc})^2$$

$$\cos \gamma_{fi} = 1 - \frac{1}{2} (\gamma_{fi})^2$$

$$\sin \gamma_{fi} = \gamma_{fi}$$

$$\sin \gamma_{fc} = \gamma_{fc}$$

By substituting, Equations (17) now become

$$\frac{h_f}{t_f} \approx \frac{1}{2} (V_{AV})_f (\gamma_{fi} + \gamma_{fc})$$

$$\frac{h_f}{x_f} \approx \frac{1}{2} (\gamma_{fi} + \gamma_{fc})$$

(18)

$$\frac{x_f}{t_f} \approx (V_{AV})_f$$

With the further assumption that γ_{fc} is close to zero so that $|\gamma_{fc}| \ll |\gamma_{fi}|$, Equation 10 becomes

$$\frac{h_f}{t_f} \approx \frac{1}{2} (V_{AV})_f \gamma_g$$

(19)

$$\frac{h_f}{x_f} \approx \frac{1}{2} \gamma_g$$

$$\frac{x_f}{t_f} \approx V_{AV}$$

where

$\gamma_g = \gamma_{fi}$ = flight path angle during equilibrium glide just prior to flare initiation

All the important flare parameters appear to be primarily a function of two parameters, the average flare velocity, $(V_{AV})_f$, and the equilibrium glide angle when the flare is initiated.

It is interesting to note that γ_g is a function of $(L/D)_{\max}$ and how far on the "frontside" of the $(L/D)_{\max}$ the flare is initiated (see Figure 18). The value of $(V_{AV})_f$ is a function of C_L for $(L/D)_{\max}$ and how much this C_L must be decreased for adequate "frontside" operation, and it is also a function of vehicle wing loading. Adequate "frontside" operation is determined by the requirements for flight path stability of Paragraph 3.2.1.3 and the requirement for adequate excess kinetic energy so that sufficient float time is available before touchdown.

The parameters of Equations (19) are interrelated, an increase in flight-path angle will result in an increase in h_i/t_f and h_f/x_f . An increase in $(V_{AV})_f$ results in an increase in h_f/t_f and h_f/x_f . The parameter x_f/t_f is probably of least concern to the pilot in unpowered landings of low $(L/D)_{\max}$ vehicles. The parameter h_f/t_f is probably of greatest concern and creates the greatest demands on the pilot in terms of timing and precision of control of the flare maneuver. The X-15 data previously presented (Figures 19b and 20b) tend to confirm the fact that as the flare altitude is reduced, the pilot prefers lower values of h_f/t_f , the average sink rate during flare.

Analysis of the Float

After completion of the flare some 50 feet above the runway surface, the float phase of the unpowered landing to touchdown begins. The float phase is conducted in nearly horizontal flight at a very low sink rate until the velocity at touchdown is approximately the velocity for $(L/D)_{\max}$ with flap and gear down (see Figure 18). Since the change in velocity is the important variable during the float, an analogous form of Equations (12) can be derived using Equations (10) and (11):

$$dt = \frac{dV}{\dot{V}}$$

$$dh = (V \sin \gamma) dt = \frac{V \sin \gamma}{\dot{V}} dV \quad (20)$$

$$dx = (V \cos \gamma) dt = \frac{V \cos \gamma}{\dot{V}} dV$$

The deceleration during the float can be determined by the first of Equations (9).

$$\begin{aligned}\frac{\dot{V}}{g} &= a_g = \left(-\frac{D}{W} - \sin \theta\right) \\ \dot{V} &= a_g g = g \left(-\frac{D}{W} - \sin \theta\right)\end{aligned}\tag{21}$$

where

a_g = longitudinal deceleration in g's

By substituting Equations (21) into Equations (20) we now have

$$\begin{aligned}dt &= \frac{dV}{g a_g} = \frac{(V \sin \theta) dV}{g \left(-\frac{D}{W} - \sin \theta\right)} \\ dh &= \frac{(V \sin \theta) dV}{g a_g} = \frac{(V \sin \theta) dV}{g \left(-\frac{D}{W} - \sin \theta\right)} \\ dx &= \frac{(V \cos \theta) dV}{g a_g} = \frac{(V \cos \theta) dV}{g \left(-\frac{D}{W} - \sin \theta\right)}\end{aligned}\tag{22}$$

If it is assumed that during the float the deceleration is reasonably constant and it can adequately be represented by an average deceleration, then

$$a_g = -\left(\frac{D}{W}\right)_{AV} - \sin \theta_{AV} = \text{constant}\tag{23}$$

During the float the following approximations are also valid:

$$\begin{aligned}\left(\frac{D}{W}\right)_{AV} &\approx \frac{1}{\left(\frac{L}{D}\right)_{AV, FL}} \\ \sin \theta_{AV} &\approx \theta_{AV, FL} \\ \cos \theta &\approx \cos \theta_{AV} = 1\end{aligned}\tag{24}$$

By substituting Equations (23) and (24) into Equations (22) we have

$$\begin{aligned}
 dt &= \frac{dV}{ga_g} = \frac{dV}{g \left[-\frac{1}{\left(\frac{L}{D}\right)_{AV,FL}} - \gamma_{AV,FL} \right]} \\
 dh &= \frac{V \gamma_{AV,FL} dV}{ga_g} = \frac{V \gamma_{AV,FL} dV}{g \left[-\frac{1}{\left(\frac{L}{D}\right)_{AV,FL}} - \gamma_{AV,FL} \right]} \\
 dx &= \frac{V dV}{ga_g} = \frac{V dV}{g \left[-\frac{1}{\left(\frac{L}{D}\right)_{AV,FL}} - \gamma_{AV,FL} \right]}
 \end{aligned} \tag{25}$$

Assuming average values of the other parameters and integrating Equations (25) only with respect to velocity we have

$$\begin{aligned}
 t_{FL} &= \frac{1}{ga_g} \int_{V_{fc}}^{V_{TD}} dV = \frac{1}{g \left[-\frac{1}{\left(\frac{L}{D}\right)_{AV,FL}} - \gamma_{AV,FL} \right]} \int_{V_{fc}}^{V_{TD}} dV \\
 &= \frac{V_{TD} - V_{fc}}{ga_g} = \frac{V_{TD} - V_{fc}}{g \left[-\frac{1}{\left(\frac{L}{D}\right)_{AV,FL}} - \gamma_{AV,FL} \right]} \\
 h_{FL} &= \frac{\gamma_{AV,FL}}{ga_g} \int_{V_{fc}}^{V_{TD}} V dV = \frac{\gamma_{AV,FL}}{g \left[-\frac{1}{\left(\frac{L}{D}\right)_{AV,FL}} - \gamma_{AV,FL} \right]} \int_{V_{fc}}^{V_{TD}} V dV \\
 &= \frac{\gamma_{AV,FL}}{2ga_g} (V_{TD}^2 - V_{fc}^2) = \frac{\gamma_{AV,FL} (V_{TD}^2 - V_{fc}^2)}{2g \left[-\frac{1}{\left(\frac{L}{D}\right)_{AV,FL}} - \gamma_{AV,FL} \right]} \\
 x_{FL} &= \frac{1}{ga_g} \int_{V_{fc}}^{V_{TD}} V dV = \frac{1}{g \left[-\frac{1}{\left(\frac{L}{D}\right)_{AV,FL}} - \gamma_{AV,FL} \right]} \int_{V_{fc}}^{V_{TD}} V dV \\
 &= \frac{V_{TD}^2 - V_{fc}^2}{2ga_g} = \frac{V_{TD}^2 - V_{fc}^2}{2g \left[-\frac{1}{\left(\frac{L}{D}\right)_{AV,FL}} - \gamma_{AV,FL} \right]}
 \end{aligned} \tag{26}$$

where

t_{FL} = float time

h_{FL} = float altitude to touchdown

x_{FL} = horizontal distance traveled during float

V_{TD} = touchdown velocity

V_{fc} = flare completion velocity which is equal to float initial velocity

$(\frac{L}{D})_{AV,FL}$ = average (L/D) during the float

$\gamma_{AV,FL}$ = average flight path angle during float

It is possible to relate the average flight path angle during the float ($\gamma_{AV,FL}$) to the average sink rate during the float ($SR_{AV,FL}$) using the first two equations of Equations (26)

$$SR_{AV,FL} = \frac{h_{FL}}{t_{FL}} = \frac{\gamma_{AV,FL} (V_{TD} + V_{fc})}{2}$$

$$\gamma_{AV,FL} = \frac{2 (SR_{AV,FL})}{(V_{TD} + V_{fc})} \quad (27)$$

The float time (t_{FL}) is directly proportional to the excess velocity, i.e., the difference between the velocity at flare completion (V_{fc}) and the touchdown velocity (V_{TD}). The touchdown velocity is determined by the C_L for $(L/D)_{max}$ during the float and the vehicle wing loading. The requirement for flight path stability during the float of Paragraph 3.2.1.3 limits the minimum touchdown speed. When the flight-path angle is negligibly small, as it usually is during the float, the float time is also proportional to $(L/D)_{AV,FL}$. $(L/D)_{AV,FL}$ is a function of $(L/D)_{max}$ during float and how far on the "frontside" of the L/D curve the float is initiated (Figure 18). Thus the role of $(L/D)_{max}$ and excess velocity in determining float time is reasonably clear.

The float distance (x_{FL}) is indicative of the runway length required for the float. Float distance is proportional to the difference in the squares of the velocities at flare completion and touchdown. Float distance is also directly proportional to $(L/D)_{AV,FL}$. Thus large float times may be undesirable in themselves but they may also be undesirable because of the proportionately larger increase in float distance.

Analysis of Data

Based on the analysis of flare parameters (Equations (18) or (19)) and the preliminary examination of X-15 data (Figure 19a), it appears that a proper relationship between flare altitude and flare time is the primary factor of importance to the pilot in the flare. Although Figure 19a includes total time to touchdown and not just flare time, the figure does suggest that the relationship between flare altitude and time is not linear, i.e., the ratio of h_f/t_f must be reduced as the flare altitude is reduced, and that a relationship between h_f/t_f exists as a function of flare altitude that will make the flare characteristics acceptable or unacceptable in varying degrees, provided the flight-path stability requirements of Paragraph 3.2.1.3 are met. An examination of the published information and discussions with Edwards personnel suggest that float time as such is important to the pilot as determined by the first of Equations (26). The float time must be long enough for the pilot to make final adjustments before touchdown, yet not so long that excessive runway is consumed in the float. Again, the unpowered float must be performed on the frontside to meet the requirements of Paragraph 3.2.1.3. The available data will be examined in the light of these flare and float parameters.

The data of Reference 30 on the first 30 flights of the X-15 were first examined in some detail to obtain flare and float characteristics during landing. In examining the X-15 data, it is assumed that the flare was completed at an elevation 50 feet above the ground. Such an assumption seems reasonable and was necessary since the flare completion point was not specified in the data. In fact, to separate the flare from the float, it was necessary to plot the data presented in Reference 30 for each X-15 landing. A time history of a typical X-15 landing in terms of altitude and velocity variation with time is shown as Figure 21. This time history was constructed from the following information available in Reference 30.

- a. Flare initiation altitude, velocity, and sink rate
- b. Velocity and altitude at which flaps were extended
- c. Velocity and altitude at which the gear was extended
- d. Flight velocity and vertical velocity at touchdown.

Figure 22a is a plot of flare time and flare altitude for the first 30 flights. The spread in the data points plotted in Figure 22a indicates the differences in flares, all successful, that can be performed by the same pilot or different pilots in unpowered landings of the same vehicle. There were 7 different pilots who participated in the first 30 flights of the X-15. Some of the differences are attributable to when the flaps and the gear were extended and how the speed brakes were used on each flight.

The data points on Figure 22a, 22b and 22c are the same. Shown on Figure 22b are lines of effective (L/D) 's for the X-15 flares based on the average velocity during the flare for all 30 flights, $(V_{av})_f = 275$ knots. The flare altitude and flare time can be related to $(L/D)_{eff}$ by the following formula:

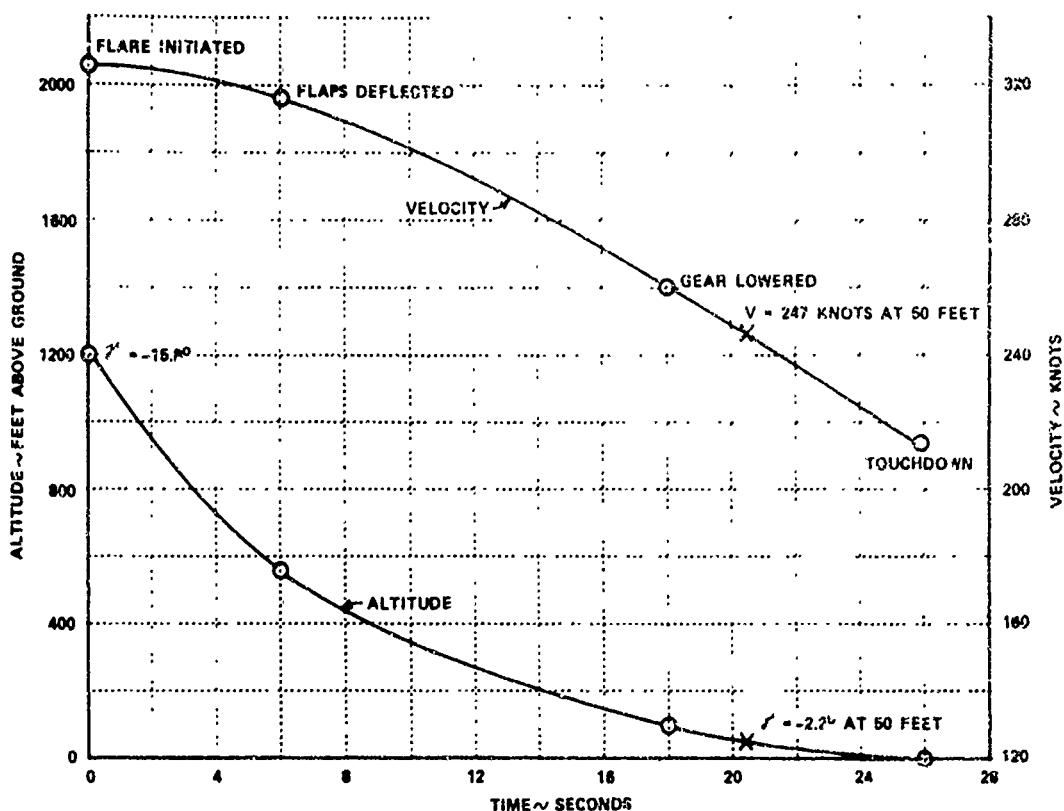


Figure 21 TYPICAL X-15 FLARE AND LANDING (REFERENCE 30)

$$\left(\frac{h_f}{t_f} \right) = \frac{(V_{AV})_f}{\sqrt{\left(\frac{L}{D} \right)_{eff}^2 + 1}} \quad (28)$$

The $(L/D)_{eff}$ represents the L/D that would be required by the X-15 to obtain a sink rate (h_f/t_f) , represented by the dotted lines, when in an equilibrium glide at 275 knots. Even though the $(L/D)_{max}$ of the X-15 is approximately 4.2 clean, the $(L/D)_{eff}$ during the flare was considerably higher and varied between 6 and 14 for the first 30 landings. One would suspect, that all other things being equal, such as adequate float time, the pilots would prefer those flares with higher $(L/D)_{eff}$'s. The high energy unpowered approach is performed on the "frontside" of the $(L/D)_{max}$ curve for improving flight path stability and to buy time during the critical float period as the excess kinetic energy is consumed. Front-side operation reduces the L/D to some value below $(L/D)_{max}$. By performing the unpowered flare the way he does, the pilot increases the "effective" L/D of the vehicle.

Figure 22c is a similar plot of the X-15 flare data except that lines of average flare flight-path angle, $(\gamma_{AV})_f$, are shown instead of $(L/D)_{eff}$. The average flare flight-path is related to h_f/t_f by the following formula:

$$\left(\frac{h_f}{t_f} \right) = (V_{AV})_f \sin(\gamma_{AV})_f \quad (29)$$

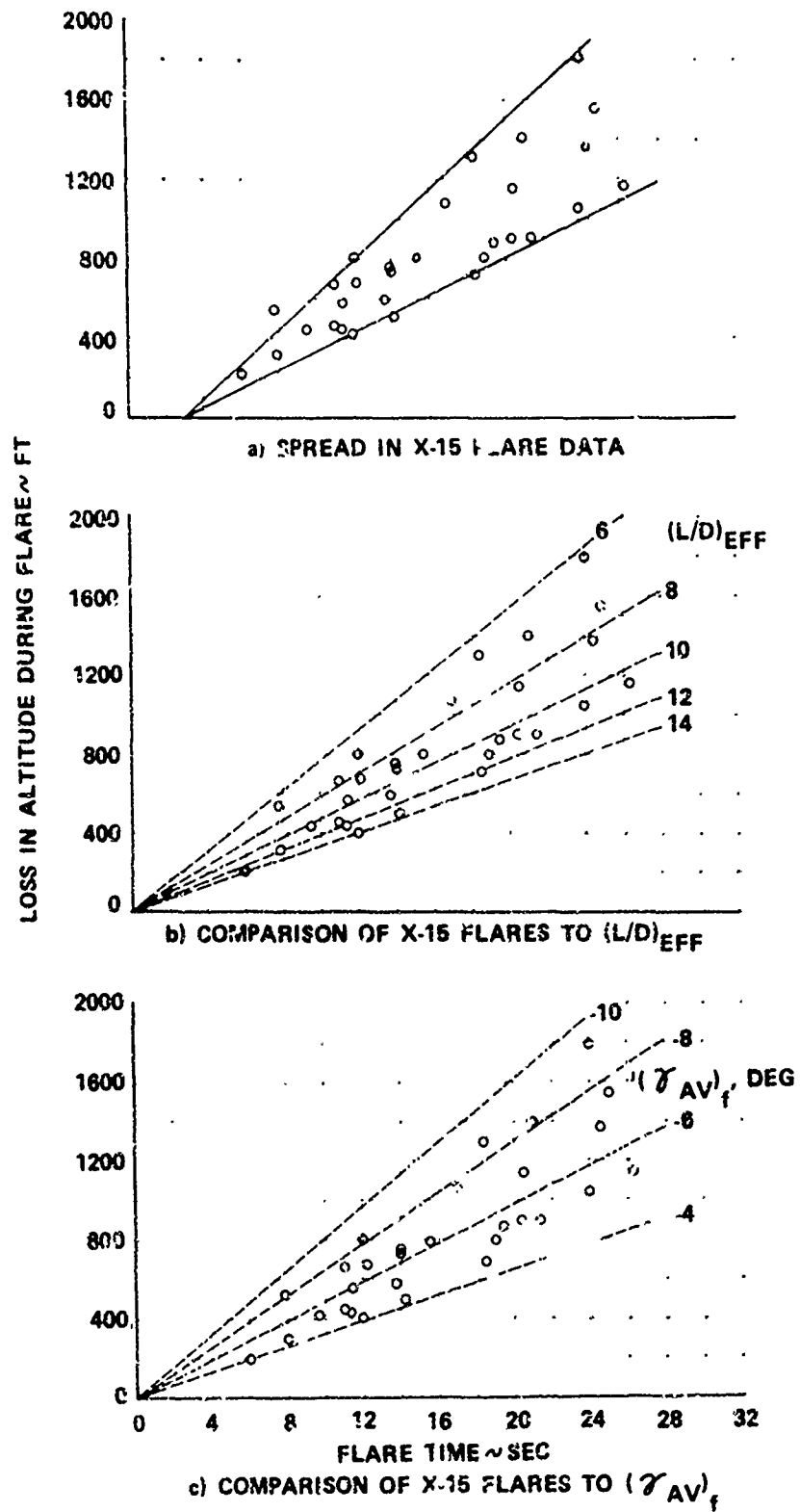


Figure 22 COMPARISON OF FLARE TIME AND FLARE ALTITUDE OF FIRST 30 FLIGHTS OF X-15 (REFERENCE 30)

Even though the average glide slope at the initiation of flare for all 30 X-15 landings was approximately -13.9° , the average glide slope during the flare varied between approximately -9 and -4 degrees. It is interesting to note that the first of Equations (19) suggests that the average flare glide slope angle is approximately one-half the equilibrium glide angle at flare initiation. This would suggest that the average glide slope for all 30 X-15 flares should be approximately $-13.9/2$ or approximately -7.0 degrees. The average of -9 degrees and -4 is -6.5 degrees, which is close to -7.0 degrees. The lower average glide slope during the flare and the higher effective L/D during the flare are really two different ways of looking at the same thing.

Figure 23 is a plot of X-15 float time (t_{FL}) or the time from flare completion to touchdown. Again the flare of the X-15 is assumed to be completed at 50 feet above ground level. Figure 23 indicates, that in general, float time increases as the flare initiation velocity is increased. This is not an unexpected result since it is excess kinetic energy which makes it possible to increase float time. Some of the scatter in the data of Figure 23 can be attributed to the difficulty of determining flare completion time or float initiation time accurately from faired curves such as Figure 21. A good deal of the scatter can also be attributed to variations in pilot handling techniques, such as how the drag brakes were modulated and when the landing gear was extended. Considerable scatter can also be attributed to variations in touchdown velocity from 153 knots to 209 knots for the 30 landings.

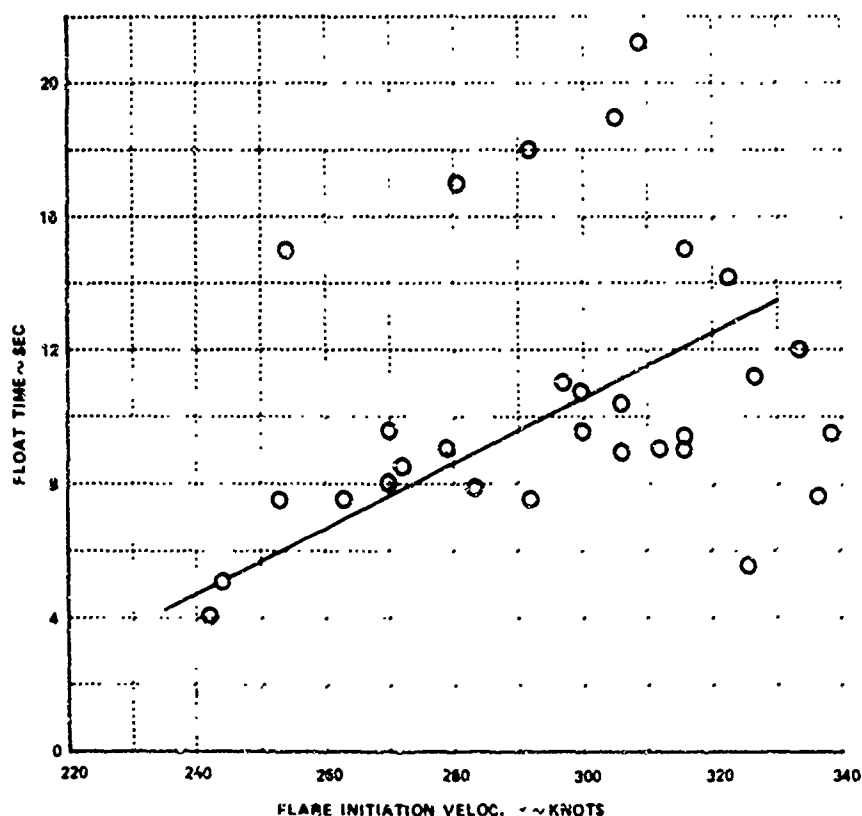


Figure 23 VARIATION OF FLOAT TIME ON FIRST 30 FLIGHTS OF X-15 (REFERENCE 30)

Reference 50 includes information on predicted flares of the M2-F2 vehicle as programmed on a six-degree-of-freedom fixed-base simulator. The altitude lost in the flare as a function of flare time is plotted as Figure 24. The flares were predicted using 9 different speeds for flare initiation and an incremental normal acceleration of 1.0 g's at flare initiation. The angle of attack at flare initiation was then held constant until the flare was completed at zero sink rate. Figure 24 also contains data runs "flown" on the same six-degree-of-freedom simulator. These data are published in Reference 34 and agree substantially with the predictions. The flares were initiated from stabilized flight-path angles and the flare initiation velocity varied from 240 to 320 knots at three different upper flap settings. All the flares were performed with an initial incremental of 1.0 g's which decreased to 0.5 g's by the end of each flare.

The flight data on the landing flares on the fifteenth and sixteenth flights, performed by the fourth and second pilots respectively, were obtained from Reference 51. The sixteenth flight was the last flight since an accident occurred and the vehicle was extensively damaged upon ground contact. The data for the flight flares are shown on Figure 24.

The comparison of flight and simulator data on M2-F2 flares is reasonably good. The handling characteristics of the M2-F2 during the landing flares are far from ideal. The magnitude of the deficiencies in landing the M2-F2 is evident from the following quotation taken directly from Reference 51.

"However, the landing task was demanding, requiring unique flight preparation and practice procedures with little margin for error or unusually increased pilot workload. Judgement of flares and landings required complete concentration."

As further evidence of the demanding nature of landing the lifting body vehicle such as the M2-F2, the first recommendation of the board convened to investigate the accident which occurred on the sixteenth flight included the following statement:

"Consideration should be given to increasing the time allotted to the pilot for the landing phase -----."

Also included in Figure 24 are flare data from a time history of the HL-10 vehicle. The data are not from any particular flight, but presumably are a composite of the flare profile flown on a typical HL-10 approach and landing. From the approximate information available in Reference 52, the flare altitude and flare time were determined.

Reference 50 is a comprehensive landing flare study of the X-24A using a six-degree-of-freedom hybrid simulation. Separate data were generated for an upper flap control law and a lower flap control law. The data are plotted as Figure 25. No flight data were available for the X-24A.

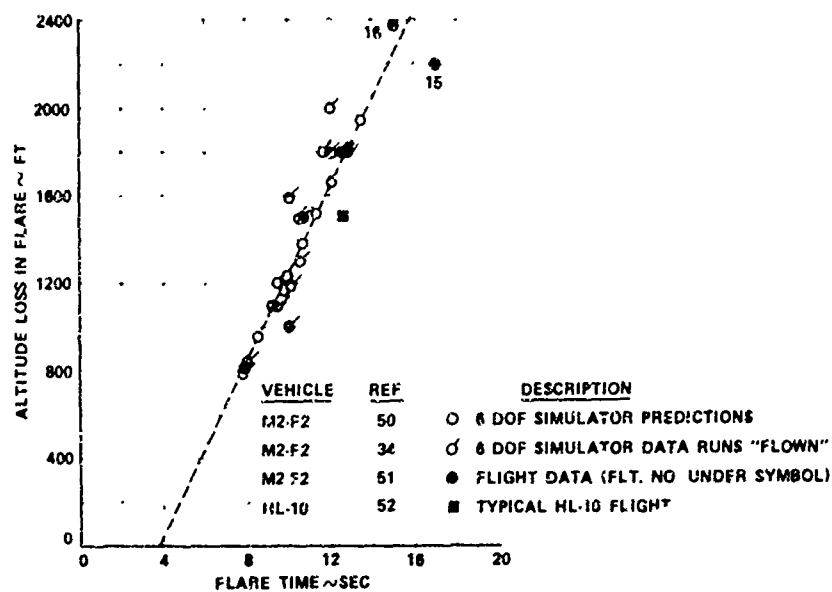


Figure 24 FLARES OF THE M2-F2 AND HL-10 VEHICLES

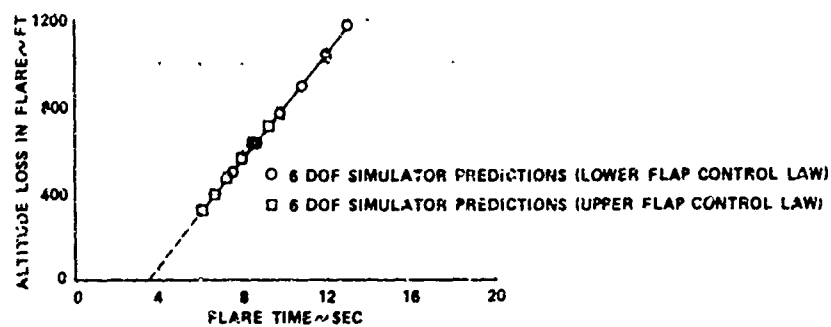


Figure 25 FLARES OF THE X-24A

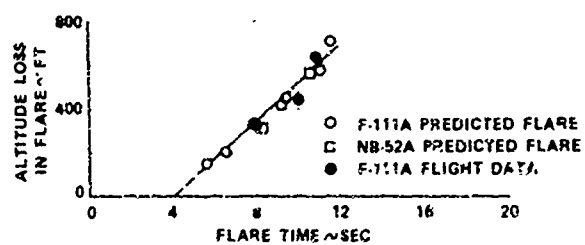


Figure 26 LOW L/D FLARES OF F-111A AND NB-52A

Reference 46 contains limited information on the flare and float of the F-111A and NB-52B aircraft performing low L/D approaches. These data are plotted in Figure 26. All the data are for predicted flares with the exception of three F-111A flares performed near the ground.

Additional information on low L/D approaches was obtained from References 53 and 47. These data are from two distinctly different aircraft, one a delta-wing interceptor and the other a straight-wing fighter. These data are plotted as Figure 27a and 27b respectively. An important assumption was made in obtaining the flare time from these data since only the combined flare and float time was given. Based on the few time histories in the reports, the average float was determined to be approximately seven seconds, based on a flare completion altitude of 50 feet above ground level.

Float time as a function of flare initiation velocity, which was obtained from many of these same references, is shown on Figure 28. The six-degree-of-freedom simulator study of the M2-F2 (Reference 34) defines float time as the time from the end of flare ($\gamma = 0^\circ$) to an airspeed of 150 knots. Flight data on M2-F2 float time (Reference 51) are also shown. The float time for a typical HL-10 flight (Reference 52) is 13 seconds. The float time from the landing flare studies of the X-24A (Reference 50) are shown. The touchdown airspeed was assumed to be 160 knots. Flight information on F-111A flares is shown and was obtained from Reference 46.

It is difficult to compare all of these data on float time since float time is a strong function of velocity at the end of flare and touchdown velocity as well as the vehicle average (L/D) during the float (Equations (26)). The data do indicate that, for any given vehicle, the float time increases as the flare initiation velocity is increased and more kinetic energy is available and is consumed during the float.

Figure 29 is a composite of the flare data presented in terms of flare time and flare altitude. Data points are not shown. The limits of the X-15 data presented on Figure 22a are shown. The faired curve through the M2-F2 data of Figure 24 and the faired curve through the X-24A data of Figure 25 are also presented. The faired curve through F-111A and the NB-52A data was obtained from Figure 26. Because of the gross assumption made in obtaining the flare times of Figure 27a and 27b, the boundaries from these data are not plotted on Figure 29.

Outside of some generalized comments on the flares and floats during unpowered landings, such as the comments previously quoted for specific vehicles, no pilot rating data and comment data exist in the references for specific flares and floats performed with these vehicles. It is therefore difficult to establish boundaries for handling qualities Levels based on the data presented. Reference 54 is a ground-based horizontal landing simulation study for low L/D glide vehicles that does contain pilot rating data and

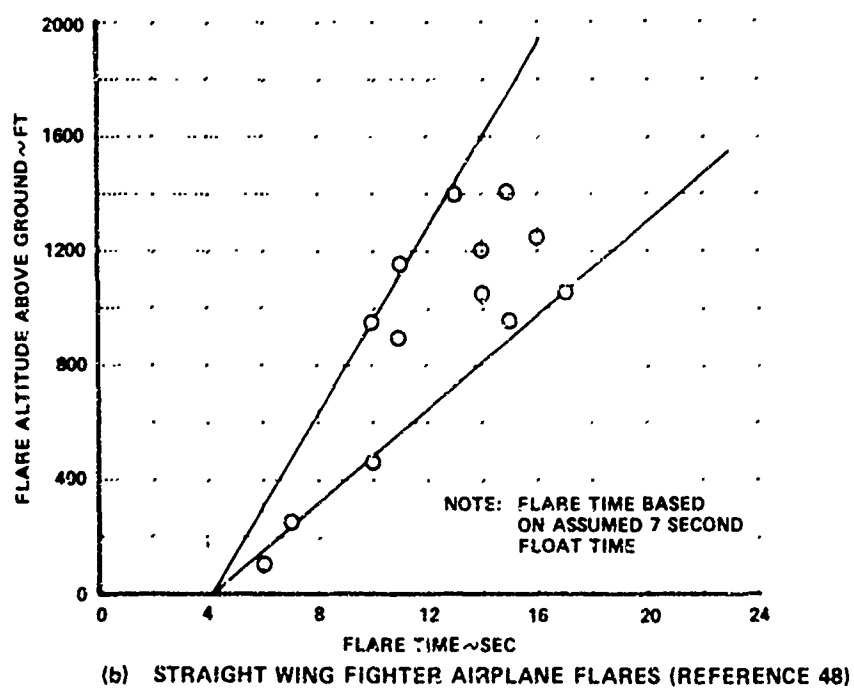
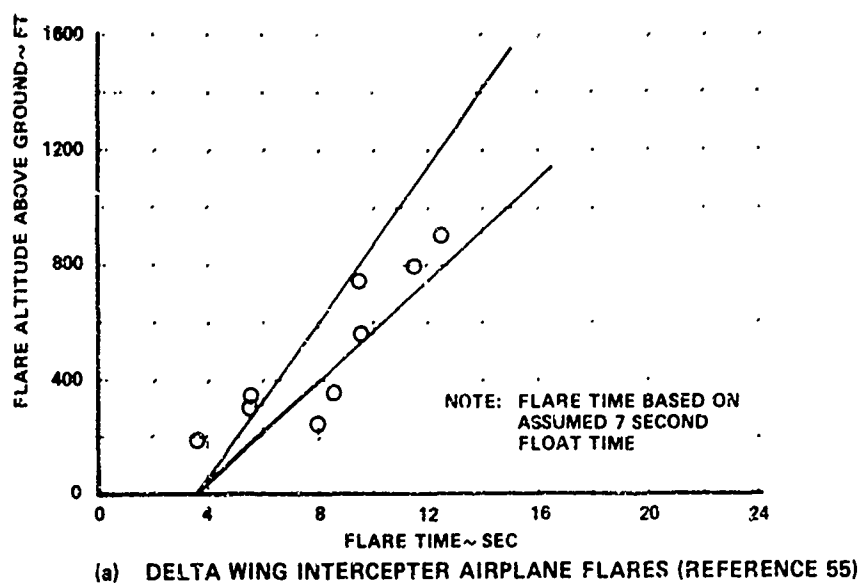


Figure 27 FLARE DATA FROM SIMULATED LOW (L/D) APPROACHES

Reference 46 contains limited information on the flare and float of the F-111A and NB-52B aircraft performing low L/D approaches. These data are plotted in Figure 26. All the data are for predicted flares with the exception of three F-111A flares performed near the ground.

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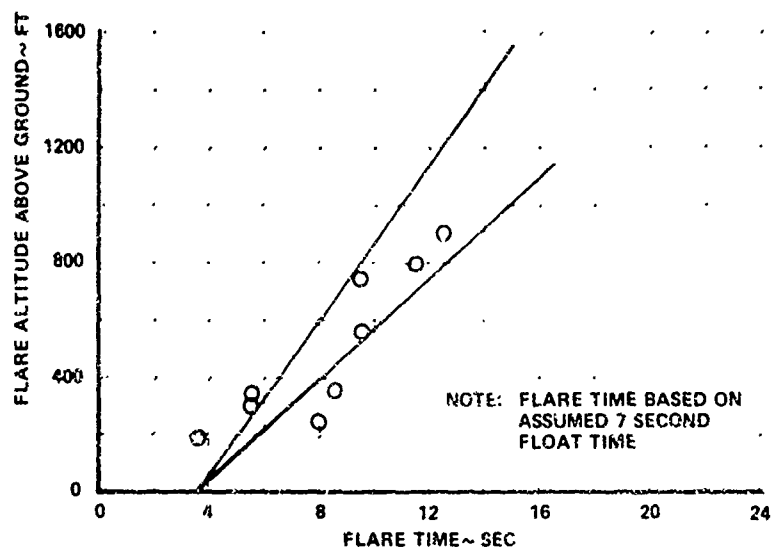
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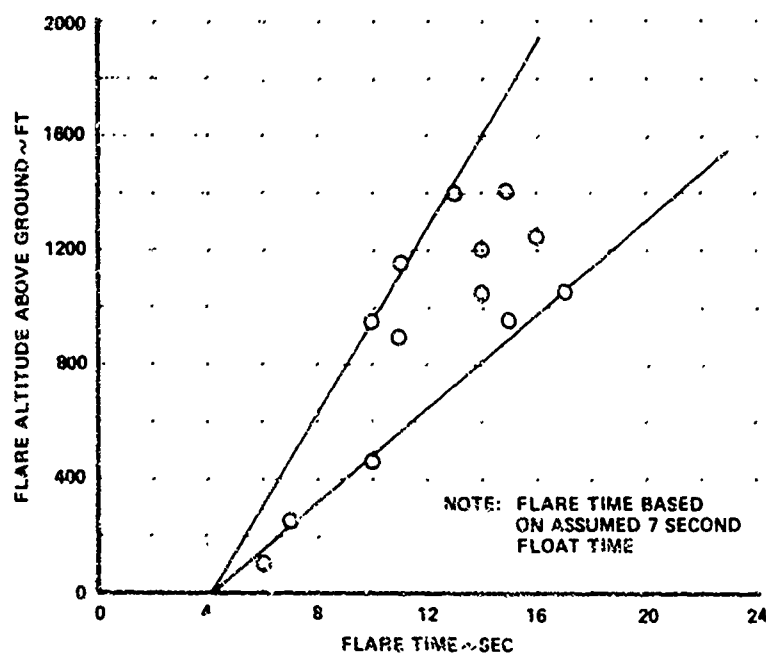
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Outside of some generalized comments on the flares and floats during unpowered landings, such as the comments previously quoted for specific vehicles, no pilot rating data and comment data exist in the references for specific flares and floats performed with these vehicles. It is therefore difficult to establish boundaries for handling qualities Levels based on the data presented. Reference 54 is a ground-based horizontal landing simulation study for low L/D glide vehicles that does contain pilot rating data and



(a) DELTA WING INTERCEPTOR AIRPLANE FLARES (REFERENCE 55)



(b) STRAIGHT WING FIGHTER AIRPLANE FLARES (REFERENCE 48)

Figure 27 FLARE DATA FROM SIMULATED LOW (L/D) APPROACHES

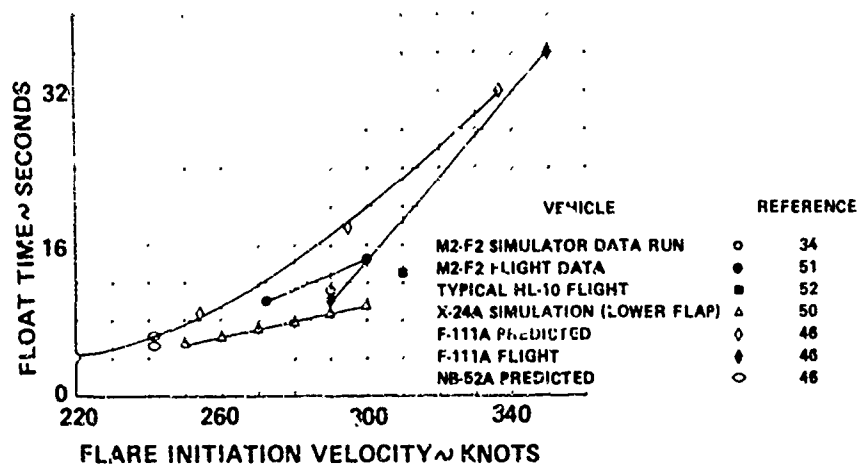


Figure 28 FLOAT TIME FOR VARIOUS VEHICLES PERFORMING UNPOWERED LANDINGS

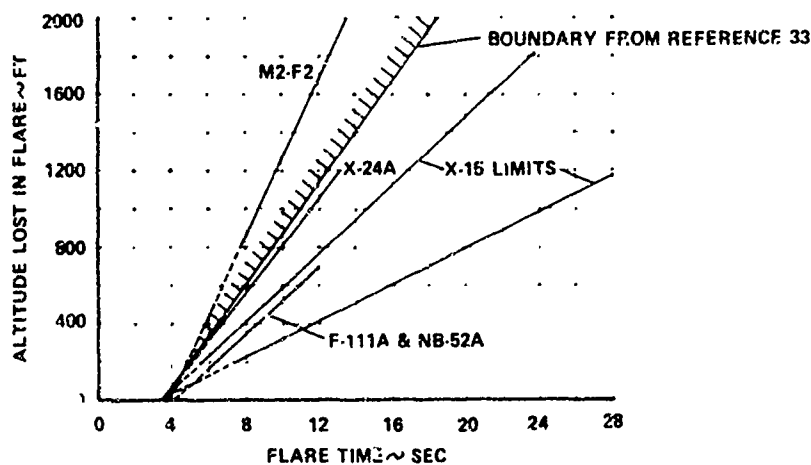


Figure 29 COMPOSITE PLOT OF FLARE DATA

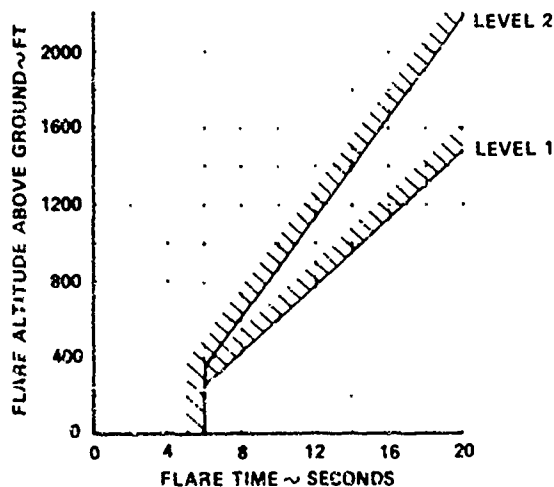


Figure 30 FLARE ALTITUDE AND FLARE TIME REQUIREMENTS FOR UNPOWERED LANDINGS (CLASS III (E) AND IV (E))

vehicles are those indicated by Figure 30. Although the data from which Figure 30 was prepared suggests a lower limit on flare time of approximately 4 seconds, no actual data extend below a flare time of 6 seconds, in fact, M2-F2 data does not extend below 8 seconds of flare time. A minimum flare time of 6 seconds appears reasonable based on available data for both Level 1 and Level 2.

While comment data upon which flare boundaries have been established for experimental vehicles were meager, no data are available for establishing similar boundaries for operational lifting re-entry vehicles.

The minimum float times contained in Table VI of the requirements (Paragraph 3.2.3.4.2) are based on the recommendations contained in Reference 49. There is evidence from other sources that indicate that these requirements are reasonable. Based on analysis and an examination of X-15 data, Reference 48 suggests "that a 15 - second margin from flare completion to touchdown is adequate". Time from flare initiation to touchdown from 18 to 23 seconds was considered ample by the lifting body pilots as reported in Reference 55. Recent conversations with lifting body pilots at Edwards Air Force Base have suggested that a total time from flare initiation to touchdown of 20 seconds is adequate. Using the minimum float time of 6 seconds shown on Figure 30, these figures suggest float times of 12 to 18 seconds and 14 seconds, respectively. All of these figures are in reasonable agreement with the minimum float requirements in Table VI.

The upper limit on float time is based on some of the considerations contained in a number of references, References 35 and 49 for example. In the unpowered approach and landing studies of Reference 35 with the CV-990, float times of 23 seconds were considered excessive. Yet, an upper limit of 30 seconds for float time in Reference 49 is said to be based on pilot opinion. Although somewhat arbitrary, 30 seconds was selected as the upper limit on float time. Excessive float time requires long runways, contributes to touchdown dispersion, and is probably dangerous.

Requirement

3.2.3.4.3 Elevator lift and longitudinal control in landing

Discussion

This is a new requirement on the effects of adverse elevator lift on altitude and flight-path control during the landing approach. Adverse elevator lift will occur with an elevator control aft of the c.g. As the elevator is deflected to change the attitude and lift of the vehicle, the initial effect of elevator lift is adverse and the initial effects on altitude and flight-path angle changes are also in the opposite direction to that intended. These effects are expected to be largest and most significant for Class III airplanes or lifting re-entry vehicles with low frequencies and large response times. The data on this subject that presently exist are insufficient and sometimes confusing from the handling qualities point of view. It is not possible to establish quantitative flying qualities requirements at this time.

boundaries based on these data. Unfortunately the boundaries are plotted in terms of overall vehicle parameters such as the $(L/D)_{\max}$ and excess preflare airspeed. The rating data are also for the complete flare and float to landing, and from the data presented it is not possible to separate the flare parameters from the float parameters.

Reference 33 contains a summary plot of a number of interrelated parameters that affect the flare and float of a low L/D unpowered glide vehicle. Various unpowered landing limits are presented based on field length, $(L/D)_{\max}$, time required for pullup, low and high flare altitude, etc., as determined from in-flight data and analytical studies. These boundaries are based on various specific assumptions discussed in detail in Reference 33. Using the information presented on the boundaries, it was possible to extract flare altitude and flare time and this boundary is plotted on Figure 29. If this boundary is considered as the boundary between acceptable and unacceptable flare characteristics, then the boundary should correlate with the data and general comments of the unpowered landings of the vehicles shown on Figure 29. The comparison shows that all the M2-F2 flare data are to the left (unacceptable) side of the boundary line, and all of the X-24A, X-15, and F-111A and NB-52A data are to the right (acceptable) side of the boundary. In summary, the boundary appears to be a reasonable Level 2 boundary for an unpowered landing of a Class IV, experimental, lifting re-entry vehicle. The generalized comments, especially those on the M2-F2, appear to support such a Level 2 boundary.

It is of interest to note from Figure 29 that all the lines intersect the zero flare altitude at between 3 and 4 seconds. This implies that there is an absolute minimum flare time of approximately 4 seconds for any vehicle no matter how large the (L/D) is. It also indicates that as the flare altitude is reduced, for any given vehicle, the pilot requires a lower average sink rate during the flare as defined by the ratio of flare altitude to flare time. This fact is not surprising and it correlates with the X-15 landing data on the first 30 flights.

The upper boundary of X-15 landing flare limits on Figure 29 agrees reasonably well with the recent limited F-111A and NB-52A data of Reference 46 on larger airplanes. Reference 46 suggests that the unpowered landing of larger airplanes is essentially no different than that of smaller lifting re-entry vehicles, but actual data on the unpowered flares of large airplanes is extremely limited. There is nothing in the literature to suggest that flares on all three of these airplanes are particularly difficult for an experimental test pilot. Reference 29 states that "although the landings (X-15 landings) are relatively routine, they do require exacting pilot performance and a high degree of proficiency". It would appear that the upper boundary of the X-15 flare data is a reasonable Level 1 boundary at this time for both Class III and Class IV experimental lifting re-entry vehicles.

Based on all these considerations, it would appear that the best estimate of Level 1 and Level 2 boundaries for experimental lifting re-entry

Reference 56 investigated this problem with the following short-period characteristics.

$$\omega_{n_{sp}} = 0.928 \text{ rad/sec}$$

$$\zeta_{sp} = .707$$

$$0.52 < L_{\alpha} < 0.57 \text{ 1/sec}$$

With these short-period characteristics it was possible to establish a Level 1 (Pilot Rating < 3.5) boundary as a function of control sensitivity (M_{δ_e}) and lift due to control (L_{δ_e}). Although the data were insufficient to describe the Level 1 boundary adequately, the trends in the data were evident. As L_{δ_e} increases above a moderate level, increases in M_{δ_e} are required for adequate handling qualities. As noted in the report, the boundary applies only for the basic airplane dynamics presented and would shift for other basic stability characteristics. It seems self-evident that the parameters $\omega_{n_{sp}}$, ζ_{sp} , and L_{α} as well as L_{δ_e} and M_{δ_e} are important in a closed-loop situation when the pilot is controlling altitude and flight path precisely.

In the 33rd Wright Brothers Lecture (Reference 57), the effects of size in conventional aircraft design were discussed in some detail. It is stated that flying qualities problems increase with aircraft size. From Reference 57, Figure 31 is presented and the following direct quotation is made:

"A flight situation is postulated in which the pilot has just discovered that he is below his chosen glide path during an approach to landing. The initial conventional airplane response to elevator deflection is opposite to that desired, because up elevator to decrease sink-rate first applies a net downward acceleration until increasing angle of attack produces the desired upward acceleration. If more than two seconds elapse between first control movement and recovery to original flight-path position, the flying qualities are unsatisfactory. The ability to meet this requirement is obviously influenced by many things, such as control-surface rate of deflection, tail length, lift-curve-slope, damping in pitch, and pitch inertia."

That a time delay of two seconds in flight path applies for all conditions of short-period dynamics seems highly unlikely. What is more likely to be true is that the numerical value of the time delay is a function of the short-period dynamics.

Reference 58 states that "an important longitudinal control parameter in the handling approach is the maximum control power available from trim and the change in lift associated with this amount of control power". These same parameters have been used in Reference 55 to establish a boundary between acceptable and unacceptable based on total control power ($M_{\delta_e} \delta_{e_{max}}$) and total loss in elevator lift in g's ($n_{\delta_e} \delta_{e_{max}}$). The boundary in

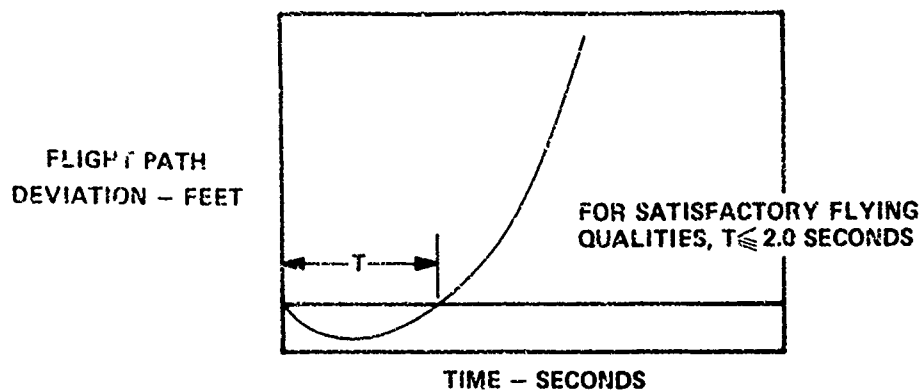


Figure 31 TYPICAL AIRPLANE RESPONSE TO ABRUPT ELEVATOR DEFLECTION (REFERENCE 57)

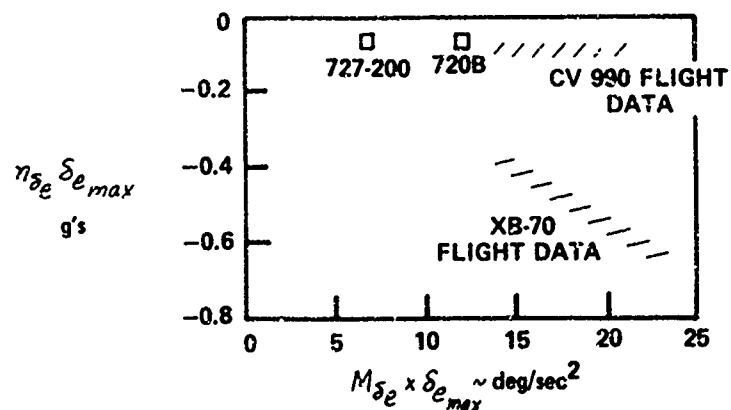


Figure 32 COMPARISON OF XB-70 LONGITUDINAL CONTROL POWER WITH THAT OF SUBSONIC JET TRANSPORTS. LANDING CONFIGURATION. (REFERENCE 58)

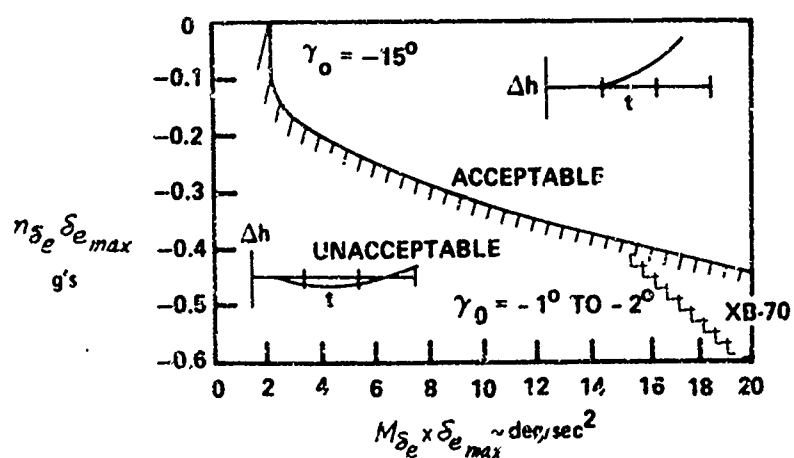


Figure 33 EFFECT OF LIFT LOSS ON LANDING CONTROL (REFERENCE 35)

Reference 35 is based on fixed-base simulations of an HL-10 Shuttle during landing approach. The HL-10 shuttle is an HL-10 lifting body scaled up to the size and weight of the Shuttle. Boundaries from both these references are shown in Figures 32 and 33.

The 727-200 and 720B data points on Figure 32 are unpublished estimates from the Boeing Company. The CV-990 data were obtained from unpublished NASA data. As stated in both references, large pitch accelerations ($M\dot{\delta}_e \delta_{e\max}$) tend to compensate for large losses in lift due to the elevator ($n\dot{\delta}_e \delta_{e\max}$).

The fact that the parameters chosen consider only total control power and total loss in lift due to the elevator, and neglect short-period dynamics, suggests that these are really not handling qualities parameters as such and that they do not adequately describe the closed-loop handling qualities situation during the landing approach. It is interesting to note that both parameters can be changed by simply varying $\delta_{e\max}$. Discussions with NASA Edwards personnel confirmed that the boundary of Figure 33 is in fact a total control boundary developed using very specific criteria. In the simulation, the pilots were asked to initiate a flare from an equilibrium glide at approximately 4,000 feet by applying full elevator control. If the pilots could, in fact, complete the flare without sinking below 2,500 feet the flare was considered acceptable; if they could not complete the flare by 2,500 feet the vehicle was considered unacceptable. Thus, what are adequate handling qualities parameters to define the effects of elevator lift loss on closed-loop control of flight path remains unresolved.

Requirements

3.2.3.5 Longitudinal control forces in dives - Service Flight Envelopes

3.2.3.6 Longitudinal control forces in dives - Permissible Flight Envelope

3.2.3.7 Longitudinal control in sideslip

Discussion

The requirements for control forces in dives in the Service and Permissible Flight Envelopes for lifting re-entry vehicles are essentially the same as the requirements for airplanes as presented in MIL-F-8785B(ASG). The only difference is that an unpowered vehicle is initially trimmed for steady glide flight. If in fact there should be longitudinal control requirements in dives for lifting re-entry vehicles, there is no rational reason evident at this time why the requirements should be different from those of conventional airplanes.

The requirements on longitudinal control in sideslip for lifting re-entry vehicles are essentially those for airplanes presented in MIL-F-8785B(ASG). The reasons are the same: small amounts of sideslip should not result in large or dangerous angle-of-attack changes nor should the corrections required by the pilot be large when he intentionally changes the sideslip angle.

Lifting re-entry vehicle configurations have a tendency to be sensitive to sideslip angle changes and the sideslip angles may be restricted because of lateral-directional requirements specified elsewhere. Under such conditions, the elevator control forces specified will apply at the maximum allowable sideslip angle.

Requirements

- 3.3 Lateral-directional flying qualities
- 3.3.1 Lateral-directional mode characteristics
- 3.3.1.1 Lateral-directional oscillations (Dutch roll)
- 3.3.1.1.1 Directional control margin

Discussion

The Dutch roll frequency and damping requirements for lifting re-entry vehicles for each Flight Phase and vehicle Class are comparable to the corresponding Flight Phase and Class of vehicle in MIL-F-8785B(ASG), Reference 2. For some of the longitudinal requirements, for example, the short-period response in Flight Phase Category C, the specifications for re-entry vehicles are more stringent than for conventional aircraft to account for the exacting task of landing an unpowered vehicle. The question naturally arises, why shouldn't the Flight Phase Category C requirements for the unpowered vehicle be more stringent for the Dutch roll, one of the primary lateral-directional modes? The answer is that the vehicle is not normally maneuvered through the Dutch roll mode. Therefore, it is not necessary to make the Dutch roll frequency and damping requirements stricter for the unpowered vehicle in Flight Phase Category C. Another reason for not making the Dutch roll requirements more stringent, in particular, the frequency requirement for Class III vehicles, is the absence of data at the lower end of the frequency spectrum. The proposed designs for the Space Shuttle Orbiter and Booster indicate that they will be very large and with their correspondingly large inertias, the vehicles will have very low Dutch roll frequencies. Since the general philosophy in compiling a specification is that requirements should not be stipulated which might limit or restrict the design when there is no rational basis or substantiative data to warrant a change, the decision was made to keep the minimum Dutch roll frequency requirements as they are in Reference 2.

The major difference between 3.3.1.1 and the same paragraph in Reference 2 is the modification to the Flight Phase Category A requirements. This change was made because of the less demanding aspects of this Phase as compared with Flight Phase Category A for conventional aircraft. As shown in Table VII, the magnitudes of the minimum frequency, minimum damping ratio and minimum total damping are the same as the Flight Phase Category C requirement.

The part of the requirement that raises the level of total damping when the parameter, $\omega_{nd}^2 / \phi / \beta_d$ is greater than 20 rad/sec², is expected to apply mostly to Class IV vehicles. The natural frequencies and roll-to-sideslip ratios of these vehicles inherently are higher than for Class III vehicles. However, when the larger vehicles are augmented to improve the bare airframe stability, the values of $\omega_{nd}^2 / \phi / \beta_d$ may approach the magnitude that requires greater total damping. In this event the requirement on the total damping must be adjusted upward by the addend, $\Delta \zeta_d \omega_{nd}$, in accordance with the appropriate equation for each handling qualities level.

The last sentence of the Dutch roll requirement in MIL-F-8785B(ASC) dictated that ω_{nd} shall always be greater than zero, with the control surfaces fixed. This statement prescribed that conventional aircraft have a short-term restoring tendency in yaw for the basic unaugmented airframe. In other words, it was necessary that aircraft have basic unaugmented "weathercock" stability. This requirement was included in the July 1970 working draft of the re-entry specification, Reference 9, but was eliminated from the present version so as not to discourage or restrict the design of various kinds of vehicles, in particular the Space Shuttle Orbiter and Booster. The decision not to require "bare" airframe stability with controls fixed was arrived at after meetings with interested government agencies and contractors associated with the Space Shuttle program. It might appear, at first, that the decision was capricious and unjustified. However, after looking at Table VII, it is obvious that the requirements specify a positive stability margin, albeit, artificially through an augmentation system. As long as stability augmentation control systems fall within the reliability standards required for each level of flying qualities, it is not necessary to require any inherent stability for the basic airframe.

The subparagraph 3.3.1.1.1, Directional control margin, is a new section written so that there is some control over the amount of directional instability that is permitted in re-entry vehicle design. When an automatic device is used to overcome an aperiodic instability of the basic vehicle, there exists a possibility of not being able to recover the vehicle during maneuvering. The reason for this anomaly is simply that the augmentation system uses control power in the recovery direction to stabilize the vehicle. If a large amount of instability is present, much of the rudder control power may be needed for stabilization and trim and little may be available for maneuvering and recovering. Obviously, some amount of control power should be available to counteract abnormal disturbances or inadvertent inputs. How much of the total control power should be available for contingencies is an interesting subject. It was initially intended to include a quantitative requirement which specified that at least 25 percent of the total rudder control power should be available to the pilot in the critical direction. This amount is specified in Reference 62 in a paragraph called "Maneuvering control margin" which is concerned with pitch control effectiveness of V/STOL aircraft. The same value is also consistent with 3.3.6.3.2, Positive effective dihedral limit, in which 25 percent of roll control power is required for sideslip angles that might be experienced in service deployment. However, until some basic research to determine the amount of rudder control power that should

be available at all times for maneuvering and control is performed, only a qualitative statement is made in 3.3.1.1.1.

Requirement

3.3.1.2 Roll mode

Discussion

The roll mode time constant requirements for Class III and Class IV operational vehicles are identical to the τ_R requirements in Reference 2. It was anticipated, at first, that the roll damping requirements would be made more stringent for the terminal Flight Phase because the parameter τ_R is important in lateral maneuvering including tasks that required preciseness in bank angle control. This idea was thought to be correct particularly for a re-entry vehicle flying an unpowered approach during which the pilot has to make very precise control inputs and has to compensate for turbulence and varying crosswind conditions. However, an examination of the specification for conventional aircraft showed the roll mode time constant requirements to be identical for Flight Phase Categories A and C. Since it is difficult to believe that the τ_R requirements should be more stringent than the values specified for the tasks that required precision tracking and precise flight-path control, which Flight Phase Category A demands in MIL-F-8785B(ASG), the τ_R requirements for operational re-entry vehicles were kept the same as for conventional aircraft.

The roll mode time constant requirements for the experimental re-entry vehicles were relaxed significantly for all three Levels of flying qualities. The τ_R maximums were increased over those specified for the operational vehicle because highly skilled test pilots will be flying the experimental vehicles in idealized environmental conditions. It is expected that the pilots will be flying the unpowered approaches and landings only in small crosswinds and in a low turbulence level like the present generation of experimental lifting re-entry vehicles, the M2-F3, HL-10 and X-24A, are flown. Under these conditions, the higher roll mode time constant for each Level of flying qualities seems reasonable for experimental re-entry vehicles.

Requirement

3.3.1.3 Spiral stability

Discussion

One major difference between the re-entry spiral stability requirements and similar requirements in MIL-F-8785B(ASG), Reference 2, is the Flight Phase Category A, Level 1 requirement for Class IV vehicles. This requirement is specified slightly more stringent for re-entry vehicles because it is assumed that the pilot may not be closing as tight a bank-angle-attitude-to-aileron loop. Unlike re-entry vehicles, Category A tasks for conventional aircraft demand rapid maneuvering, precision tracking or precise flight-path con-

trol. Since the pilot flying re-entry vehicles during Category A Flight Phases may not be continuously controlling bank angle or may not be controlling it precisely or rapidly, then less spiral instability should be permitted.

Consideration was given to relaxing the Flight Phase Category C, Level 1 requirements for both vehicle Classes, because the pilot flying the terminal phase of a re-entry mission would be holding his bank angle very precisely. With this technique, a higher level of spiral instability could be allowed. However, conventional aircraft are usually controlled very tightly during the landing approach, flare and touchdown and yet a $T_2 \geq 20$ seconds is specified in Reference 2. Therefore, without further information or new data, the Flight Phase Category C, Level 1 requirements for re-entry vehicles were left the same as for Class III and Class IV conventional aircraft.

Additional requirements are included for the experimental vehicles in recognition of the fact that these vehicles are expected to be controlled very positively at all times. Therefore the spiral stability requirements specified for the experimental vehicle are more lenient than for the operational vehicle. The values of the minimum time to double amplitude for Class III-E and Class IV-E vehicles listed in Table IX are consistent with the magnitudes specified in Reference 9.

Requirement

3.3.1.4 Coupled roll-spiral oscillation

Discussion

The authors of MIL-F-8785B did consider allowing a coupled roll-spiral mode for Level 3 flying qualities. In fact, an early draft of the specification permitted this secondary lateral-directional oscillatory mode provided $(\xi \omega_n)_{25}$ was greater than 0.1. The final version of the specification for conventional aircraft does not permit the coupled roll-spiral mode even though data are presented in Reference 8 which indicate that some coupled roll-spiral mode configurations received acceptable ratings. Not enough information was available to justify permitting the mode, in particular when at the same time other handling qualities might not be satisfactory. One other pertinent factor is turbulence and how this phenomenon can drastically affect the pilot rating of a configuration with a coupled roll-spiral mode. This effect was documented in Reference 60, an in-flight simulation experiment performed for the re-entry mission. In this study a difference of up to 4.5 in pilot ratings was given for the same configuration when evaluated in turbulence as compared to an evaluation in smooth air. One coupled roll-spiral configuration received a pilot rating of 5 in smooth air and 9.5 when flown in moderate turbulence. Based on the foregoing, no coupled roll-spiral mode will be permitted for re-entry vehicles.

Requirement

3.3.2 Lateral-directional dynamic response characteristics

Discussion

As it is in the flying qualities specification for conventional aircraft, Reference 2, the lateral-directional dynamic response characteristics for re-entry vehicles have been divided into five main groupings as follows: (1) response to atmospheric disturbances, 2) roll rate and bank angle oscillations, 3) sideslip excursions, 4) control of sideslip in rolls, and 5) turn coordination. The latter two subjects are concerned with the maximum aileron and rudder cockpit control forces permitted in improving the rolling and yawing motions. The characteristics of the first three subjects are related to the roll-to-sideslip ratio of the Dutch roll mode ($|\phi/\beta|_d$). For example, when $|\phi/\beta|_d$ is in the high to very high range, the response to atmospheric disturbances will be the most important consideration. Correspondingly, for low values of $|\phi/\beta|_d$, sideslip excursions will be the parameter of most concern. The roll rate and bank angle oscillations requirements will be most applicable whenever $|\phi/\beta|_d$ is in the moderate to high range, the response to atmospheric disturbances will be the most important consideration. Correspondingly, for low values of $|\phi/\beta|_d$, sideslip excursions will be the parameter of most concern. The roll rate and bank angle oscillation requirements will be most applicable whenever $|\phi/\beta|_d$ is in the moderate to high range. Since most re-entry vehicle designs presently conceived have moderate and higher values of $|\phi/\beta|_d$, the important lateral-directional dynamic response characteristics paragraphs will be the ones that specify response to atmospheric disturbances and the roll rate and bank angle oscillation requirements.

Requirement

3.3.2.1 Lateral-directional response to atmospheric disturbances

Discussion

The lateral-directional response to atmospheric disturbances could be the most critical aspect of an unpowered re-entry configuration, particularly in the terminal Flight Phases where turbulence and wind shear effects are most prevalent. Even though many characteristics such as the Dutch roll natural frequency, the Dutch roll damping ratio, the roll mode time constant, the phase relationship between roll rate and sideslip angle, the roll-to-sideslip ratio of the Dutch roll mode, the flight-control system nonlinearities and the combined effects and interactions between these parameters determine the lateral-directional response to atmospheric disturbances, one of these parameters, $|\phi/\beta|_d$, is likely to be of primary importance when it falls within the high to very high range. Most of the Class IV and some of the Class III re-entry vehicle configurations have $|\phi/\beta|_d$ which fall within this range. Therefore a substantial number of re-entry vehicles will have a large response to atmospheric disturbances and the requirement of 3.3.2.1 may be one of the most im-

portant for these vehicles. It is unfortunate that only qualitative requirements are specified in Reference 2 and that the re-entry requirements are also qualitative. Until some research is accomplished on the lateral-directional response to atmospheric disturbances for vehicles with very high $|\phi/\beta|_d$, no quantitative requirements can be specified.

Incidentally, the $\Delta \dot{\gamma}_d \omega_{nd} = f(\omega_{nd}^2 |\phi/\beta|_d)$ requirement of 3.3.1.1 can be considered a crude requirement to improve the response in turbulence since it requires an increase in Dutch roll damping as $(\omega_{nd}^2 |\phi/\beta|_d)$ gets large. However, as mentioned in the discussion of 3.3.2.1 in Reference 8, because the controllability in turbulence is not a simple problem, a mere increase in the Dutch roll damping may not be a satisfactory solution.

The last sentence of the requirement leaves the specification of the different types and magnitudes of atmospheric disturbances for an operational vehicle and an experimental vehicle up to the procuring activity. If a suitable method for specifying the lateral-directional response to atmospheric disturbances is developed, then quantitative requirements on disturbances and parameters can be specified. It should be noted that the bounds on the requirements will probably vary significantly depending on whether the mission for the re-entry vehicle is operational or experimental.

Requirements

3.3.2.2 Roll rate oscillations

3.3.2.2.1 Additional roll rate requirements for small inputs

Discussion

These requirements are very similar to paragraphs 3.3.2.2 and 3.3.2.2.1 of MIL-F-8785B(ASG), Reference 2. As stated in Reference 8, limitations on the oscillations in roll rate are directed at precision of control of vehicles with moderate-to-high $|\phi/\beta|_d$ response ratios. Because the modal characteristics of Class III vehicles generally have roll-to-sideslip ratios of the Dutch roll that are within this range, these two lateral-directional requirements will be more applicable to this Class of vehicle than to a Class IV vehicle.

As with the roll mode time constant requirements, it was initially intended to make the requirements on roll rate oscillations more stringent for Flight Phase Category C than for Categories A and B. This change was thought necessary to account for the precision of control demanded of Flight Phase Category C tasks. In particular, landing an unpowered vehicle on a normal size runway is one task that requires precise control about all axes including the lateral-directional axes. However, on examining MIL-F-8785B(ASG), Reference 2, it was found that the requirements on roll oscillations are identical for Flight Phase Category A, the most demanding Flight Phase, and Flight Phase Category C, the next most demanding Flight Phase. Since the definition of Flight Phase Category A for conventional aircraft is similar to the definition

of Flight Phase Category C for re-entry vehicles, and the definition of Flight Phase Category C for conventional aircraft is quite similar to the definition of Flight Phase Category A for re-entry vehicles, then the roll oscillation requirements should remain the same in the re-entry specification for Flight Phase Categories A and C.

It is noteworthy that the data used to substantiate the requirements for Flight Phase Category B in MIL-F-8785B(ASG) were obtained from two in-flight research programs (References 60 and 61) that simulated the re-entry mission. So the Flight Phase Category B requirements in MIL-F-8785B(ASG) are especially pertinent and directly applicable to re-entry vehicles. Unfortunately, few data points are located in the vicinity of the Level 2 boundary for the phase angles that relate to the adverse yaw region. As a result, the boundary of $\rho_{osc}/\rho_{AV} = 1.0$ which prohibits roll rate reversal may seem arbitrary. However, this requirement is consistent with the former MIL-F-3785(ASG) document which prohibited roll rate reversals during rudder-free rolls. Since no additional information or new data exists, the Flight Phase Category B roll rate oscillation restriction for re-entry vehicles was kept the same as the requirement for conventional aircraft.

It might be fitting to compile a short summary of the rationale or background information concerning paragraphs 3.3.2.2 and 3.3.2.2.1. Some of the highlights are listed as follows:

- a. Because Class III and Class IV re-entry vehicles generally have $|\dot{\phi}/\dot{\psi}|_d$ response ratios in the moderate-to-high range, paragraphs 3.3.2.2 and 3.3.2.2.1 are of primary concern and are directly applicable to both Classes of re-entry vehicles.
- b. The re-entry vehicle roll rate oscillation requirements for Flight Phase Category A are identical to those for Flight Phase Category C. The requirements are also similar for the comparable Flight Phases in MIL-F-8785B(ASG).
- c. For Flight Phase Category B, the requirements specified for conventional aircraft are directly applicable to re-entry vehicles since the data used to establish the MIL-F-8785B(ASG) boundaries were generated exclusively from research programs that simulated the re-entry mission.

Requirement

3.3.2.3 Bank angle oscillations

Discussion

The bank angle oscillation requirements are the same as in MIL-F-8785B(ASG) and are very similar to the requirements of 3.3.2.2.1. As stated in Reference 8, the bank angle time history from a pulse is essentially the same as the roll rate time history following a step input. With this knowledge,

the authors of MIL-F-8785B(ASG) transformed the ρ_{osc}/ρ_{AV} requirements of Figure 4 into the ϕ_{osc}/ϕ_{AV} requirements of Figure 5. The movement of the boundaries was accomplished simply by displacing the ψ_β parameter in Figure 4 to the left by a value equivalent to the angle $(90 + \sin^{-1} \zeta_d)$ degrees. The advantage of having paragraph 3.3.2.3 is that large aileron control command inputs can be inserted without the vehicle rolling to excessive bank angles. A secondary reason is that ψ_β will be easier to measure because the sideslip trace will not ramp. Ramping, the almost constant buildup of the median sideslip angle with time, is one of the major difficulties that the user must face in assessing a vehicle's roll rate oscillatory characteristics, particularly when a vehicle has a noticeably divergent spiral. After considering all the advantages that the ϕ_{osc}/ϕ_{AV} requirements have over ρ_{osc}/ρ_{AV} ones, it might seem that paragraph 3.3.2.2.1 is not necessary. This could be true were it not for certain augmentation systems, for example, a stick-position-dependent roll damping augmentation system. Such a system could be mechanized to provide roll damping around the neutral position but when the stick is deflected beyond the threshold region, roll damping is cut out. When a step aileron control command is made, the ensuing roll rate oscillations are independent of the roll damping augmentation; whereas, for an aileron control command impulse, the bank angle oscillations generated are affected continuously by the roll damping augmentation system once the pulse is removed. Hence no correlation could be expected from the two tests for roll oscillatory characteristics. In summary, even though the ϕ_{osc}/ϕ_{AV} requirements for a command impulse are essentially the same as the ρ_{osc}/ρ_{AV} requirements for a step input, both sets of requirements should be included to preclude the presence of a gap in the specifications for some sophisticated control system mechanizations.

Requirements

3.3.2.4 Sideslip excursions

3.3.2.4.1 Additional sideslip requirements for small inputs

Discussion

As emphasized in the general discussion of the lateral-directional dynamic characteristics, for vehicles with a low $|\phi/\beta|_d$ ratio, the sideslip response is the predominant undesired lateral-directional motion that results from an aileron control input. Obviously, paragraphs 3.3.2.4 and 3.3.2.4.1 that set limits on the magnitude of sideslip allowed are most meaningful to vehicles that exhibit low roll-to-sideslip response ratios. Since the majority of lifting re-entry vehicles have high $|\phi'/\beta|_d$ ratios, the sideslip requirements are not expected to be critical requirements for these vehicles. It should not be construed from this statement, however, that sideslip is unimportant or its effect should be downrated. On the contrary, the reaction to even small sideslips can be very dramatic, but the primary effect will show up in the lateral axis. As a result, the significant factors influencing the design of the lateral-directional properties of the majority of re-entry vehicles will probably be the roll rate and bank angle oscillations and not the sideslip excursions.

Initially, a major revamping of the sideslip excursion requirements in MIL-F-8785B(ASG), Reference 2, was considered. The proposed modification consisted of changing the parameter $\Delta\beta_{\max}$ to $|\Delta\beta/\phi_i| \times |\phi/\beta|_d$ which is used in MIL-F-83300, Reference 62. This latter parameter is the product of the ratio of the maximum change in sideslip angle to the initial peak in the bank angle response and the ratio of the instantaneous roll-to-sideslip angle envelopes of the Dutch roll mode. The primary reasons for considering the new parameter are the pragmatic difficulties of using the scaling parameter " ϵ " and its dependence on 3.3.4, the roll control effectiveness requirements. This form of the requirement recognizes the need for a tie between sideslip, the undesired motion, and roll, the desired response, by using ϕ_i , the initial peak magnitude in bank angle as the measure of roll response to the aileron input. With this form of the requirement it is no longer necessary to calculate (ϕ_i) command and (ϕ_i) requirement and ratio one to the other. Incidentally, attention is directed to the fact that ϕ_i is not the bank angle change achieved in one second as defined in Reference 2.

The reason $|\Delta\beta/\phi_i| \times |\phi/\beta|_d$ was not employed instead of $\Delta\beta_{\max}$ is that the requirement of 3.3.8.2 in Reference 62 was formulated only for aileron control pulse inputs. The sideslip excursions resulting from step aileron control inputs may also be important depending on how the stability augmentation system is mechanized. Therefore an attempt was made to modify the requirement so it would be usable for step aileron control commands. It was hypothesized that some parameter like $|\Delta\beta/p_i| \times |\phi/\beta|_d$ where p_i is the initial peak magnitude in roll rate response, might be acceptable in deriving a requirement that could be demonstrated with a step aileron control command. However, in attempting to check this concept, the magnitude of the task soon became apparent. As a minimum, it would be necessary to convert all the extensive sideslip excursion data used in References 2 and 62. This conversion would require extensive use of computer time and programs followed by much additional effort in correlating the data with the proposed boundaries for different Flight Phase Categories and Levels of flying qualities. The decision was made not to perform this work but rather to concentrate on other more important paragraphs in the specification, e.g., the critical flare and float requirements for unpowered vehicles. Therefore the validity of the parameter $|\Delta\beta/p_i| \times |\phi/\beta|_d$ is still unknown since it has not been tested.

The sideslip requirements utilizing the parameter $\Delta\beta_{\max}$ differ from the comparable requirements in MIL-F-8785B(ASG), Reference 2, in that the magnitude of the requirement for re-entry vehicles in Flight Phase Category C is stricter and in Flight Phase Category A is more lenient than for conventional aircraft. Since the definition of Flight Phase Category C for re-entry vehicles is closer to the definition of Flight Phase Category A for conventional aircraft, then the limits on the maximum sideslip allowed for re-entry vehicles in the terminal Flight Phases are the same as the Category A nonterminal Flight Phases in Reference 2. Likewise, the $\Delta\beta_{\max}$ limits for re-entry vehicles in Flight Phase Category A are identical to Flight Phase Category C for conventional aircraft since the definitions of the Flight Phase categories are somewhat similar.

The data used to substantiate the requirements for Flight Phase Category B in MIL-F-8785B(ASG), Reference 2, were obtained exclusively from an in-flight research program (Reference 61) that simulated the lateral-directional handling qualities of entry vehicles. Hence the sideslip excursion boundaries for Flight Phase Category B in the specification for conventional aircraft are directly applicable to re-entry vehicles. The research of Reference 61 involved a wide variety of lateral-directional characteristics including Dutch roll damping ratio from .1 to .5 and Dutch roll natural frequencies from 1.0 to about 4 radians per second. No data were used unless the roll-to-sideslip ratio of the Dutch roll mode was less than approximately 2.5. The reason for excluding data with higher $|\phi/\beta|_d$ is because the pilot ratings associated with these simulations would reflect problems in roll rate oscillations, bank angle oscillations, or response to turbulence rather than sideslip excursion problems. In summary, until further information becomes available, the sideslip excursion requirements for re-entry vehicles in Flight Phase Category B remain the same as specified for conventional aircraft.

As is true of the roll rate oscillations requirement of 3.3.2.2.1, the sideslip excursion requirements of 3.3.2.4.1 are applicable only to small inputs. It is obviously important to have requirements for both small and large control inputs, because a certain degree of precision of control is needed for small as well as large control input maneuvers. The requirement for large inputs of 3.3.2.4 was derived from 3.3.2.4.1 and might appear to be redundant but paragraph 3.3.2.4 is obviously a necessary complement to that part of the specification directed at the unwanted response, sideslip excursions for both large and small control inputs.

The primary purpose of the parameter, ϵ , is to scale the permissible sideslip when either the aileron control input is small or else the applicable requirement in 3.3.4 cannot be satisfied. Thus, with the use of ϵ , the sideslip excursion requirement can still be applied even though the vehicle cannot meet the roll control effectiveness requirement. In Reference 2, no upper bound was placed on the " ϵ " parameter. The reason for this decision is consistent with the argument that if roll performance is in excess of the appropriate requirement, then the unwanted sideslip should also be allowed to increase. However, with no upper limit on ϵ , the maximum allowable sideslip could reach inordinately high values. As an example, attention is directed at the roll control effectiveness requirement for Class III-E vehicles, Flight Phase Category A, Level 2. From Table X, $\phi_r = 30^\circ$ in 3.1 seconds. Also from paragraph 3.3.2.4, the sideslip excursion requirement is $\Delta\beta_{\max} = 15\epsilon$ degrees. Now suppose the vehicle has very effective ailerons and it can achieve a bank angle of 60 degrees in 3.1 seconds. The scaling parameter is then calculated as $60/30$ or 2. Knowing this value for ϵ , the maximum allowable sideslip angle is $\Delta\beta_{\max} = 15\epsilon = 15 \times 2$ or 30 degrees, a rather large sideslip angle. In order to limit the sideslip angle in these cases where the roll requirements are easily exceeded, the latter part of 3.3.2.4 is included as an important aspect of the sideslip excursion requirement. In this sentence, regardless of how effective the ailerons are, the scaling parameter (ϵ) is restricted to values equal to or less than unity. In other words, when the roll performance exceeds the requirements of 3.3.4 the maximum amount of sideslip allowed shall be determined assuming $\epsilon = 1.0$.

Requirement

3.3.2.5 Control of sideslip in rolls

Discussion

This paragraph places reasonable limits on the maximum rudder pedal forces permitted to maintain zero sideslip during the rapid turn entries described in the roll control effectiveness requirements. The strictest requirement is specified for Flight Phase Category C, Level 1 because it is important that any sideslip generated can be compensated for with little pilot effort during the critical terminal Flight Phases.

Requirement

3.3.2.6 Turn coordination

Discussion

The forces required to accomplish coordinated turns were specified to ensure that only modest rudder and aileron forces are necessary when performing the maneuver. It is reasonable that the pilot of a Class IV vehicle be able to coordinate a turn using a bank angle of up to 60 degrees and the pilot of a Class III vehicle be able to coordinate a 30 degree banked turn without exceeding the rudder and aileron force limitations specified for coordination.

Requirement

3.3.3 Pilot-induced oscillations

Discussion

This paragraph is quite similar to 3.2.2.3, the longitudinal pilot-induced oscillations requirement. As it is true for the longitudinal case, it is equally important that zero or negative lateral-directional closed-loop damping situations not be tolerated for any vehicle Class, flight condition or failure state. The requirement should apply whether the oscillations are caused by vehicle dynamics, control system dynamics, friction, free play, aeroelastic coupling, or any combination of these and other characteristics of the complete vehicle system.

Requirement

3.3.4 Roll control effectiveness

Discussion

Adequate roll control effectiveness is of fundamental importance to airplanes and lifting re-entry vehicles. Adequate control power is necessary

for general maneuverability in roll, trimming the vehicle laterally in crosswinds, and correcting for lateral upsets due to atmospheric disturbances. Control with atmospheric disturbances is of special significance, because, as brought out in the discussion of the lateral-directional dynamic response characteristics with a high $|\phi/\beta|_d$, lifting re-entry vehicles tend to be very susceptible to turbulence. The ability of the pilot to compensate for turbulence is highly dependent on the dynamics of the vehicle, the augmentation system installed and its sensitivity to turbulence, and the specific atmospheric environment in which the vehicle must fly.

Roll control effectiveness to satisfy general maneuverability needs during the various Flight Phases is the primary requirement covered by this paragraph (3.3.4). Roll control requirements to balance the vehicle due to dihedral effects are covered by 3.3.6.3.2. Roll control in crosswinds during final approach is covered in 3.3.7.1. The roll control shall also be sufficient to balance the vehicle in roll throughout the Service Flight Envelope in the atmospheric disturbances of 3.7.3 and 3.7.4 for the operational vehicle. A reduced atmospheric disturbance level is allowed for the experimental vehicle. One or more of these requirements will determine the maximum roll control effectiveness that is needed by a lifting re-entry vehicle.

Roll control effectiveness for general vulnerability is a function of vehicle class, whether the vehicle is operational or experimental, the Flight Phase Category, and the Level of flying qualities. Because of these interrelationships, a large number of quantitative requirements are specified in Table X for roll control effectiveness.

In keeping with the approach used in Reference 8 for airplanes, the roll control effectiveness requirements have been specified in terms of time to bank to a characteristic bank angle as a function of vehicle Class and Flight Phase Category. For Class III re-entry vehicles, a 30-degree bank angle is probably representative of bank angles used for Flight Phase Category A and B tasks. For Class IV vehicles 45 degrees of bank is probably more appropriate for these same two Flight Phases. Since re-entry vehicles, particularly unpowered vehicles, will require a reasonable degree of maneuverability during Flight Phase C, a characteristic bank angle of 45 degrees is considered appropriate for both Class III and Class IV vehicles.

It was necessary to devise a rational method for determining roll control effectiveness requirements for re-entry vehicles using essentially the requirements for airplanes as they appear in MIL-F-8785B(ASG). The method consists of first converting the roll control effectiveness requirements for airplanes in Table IX of MIL-F-8785B(ASG), presented in terms of time to attain a characteristic bank angle, to roll control power requirements. The roll control power requirements of airplanes and lifting re-entry vehicles were next related by establishing some rational method of relating the Flight Phases of airplanes and lifting re-entry vehicles. Once this was done, the roll control powers established for lifting re-entry vehicles were converted to roll control effectiveness requirements, based on time to attain the characteristic bank angle established for re-entry vehicles.

Based on a one-degree-of-freedom roll analysis, the roll control power ($L_{\delta_a} \delta_a$) is equal to the initial roll acceleration ($\dot{\phi}_0$) for a step aileron control input (δ_a). The roll control power or the initial roll acceleration required to attain a characteristic roll angle (ϕ_c) in a given time (t) is determined by the following equation

$$L_{\delta_a} \delta_a = \dot{\phi}_0 = \frac{\phi_c}{[\tau_R t - \tau_R (1 - e^{-t/\tau_R})]} \quad (30)$$

In practice it is not possible for pilots to make a perfect step aileron input. The roll performance requirements of Table IX (ϕ_c) in MIL-F-8785B(ASG) (Reference 2) are based on ramp inputs of 0.6 second for Class III airplanes and 0.2 second for Class IV airplanes. The roll performance as a function of time for a ramp input can be approximated well with a step input if the step is initiated at one-half the ramp time. The delay time (dt) for the equivalent step is 0.3 and 0.1 seconds for Class III and Class IV airplanes respectively. It was necessary to subtract these small increments of time from the times of Table IX of Reference 2 to obtain the current time (t) to be used in Equation 30 to convert the roll requirements for airplanes to roll control power or initial roll acceleration. In using Equation 30, a representative and constant τ_R of 1.0 was assumed.

The roll control power requirements for airplanes and operational lifting re-entry vehicles during Category C Flight Phases are expected to be similar because of the similarities in the piloting tasks, especially during landing. This is true for both Class III and Class IV vehicles. Category B Flight Phases for airplanes and lifting re-entry vehicles are quite similar, therefore it is reasonable to assume the same roll control power requirements for re-entry vehicles and airplanes.

Category A Flight Phases for airplanes and lifting re-entry vehicles bear little resemblance to each other. It is obvious that the roll control power requirements for Class IV airplanes are significantly larger than those for Class IV re-entry vehicles because of the differences in Category A Flight Phases and their maneuvering requirements. The same arguments apply to the difference in Category A Flight Phases of airplanes and re-entry vehicles for Class III. Category B roll control power requirements for airplanes are more representative of Category A roll control power requirements for re-entry vehicles. The decision was therefore made to make Category A and B roll control power requirements the same.

Once roll control power requirements for lifting re-entry vehicles were established as a function of vehicle Class, Flight Phase Category, and Levels, it was necessary to convert these requirements into the time required to obtain the characteristic bank angles established for lifting re-entry vehicles. Rearranging Equation (30), and again assuming a representative $\tau_R = 1.0$, we have

$$t + e^{-t} = \frac{\phi_c}{\dot{\phi}_0} + 1 \quad (31)$$

where $\dot{\phi}_0 = L_{\delta_a} \delta_a$

From a knowledge of the characteristic bank angle and the roll control power ($\dot{\phi}_0 = L_{\delta_a} \delta_a$) it is possible to determine the time required to obtain the characteristic bank angle. These values are shown in Table X as a function of vehicle Class, Flight Phase Category, and Level. It is interesting to note that in Table X the roll control effectiveness requirements of experimental vehicles are the same as those of operational vehicles. The rationale will be presented later.

One of the determining factors in establishing roll control effectiveness requirements for Flight Phase Category C is the capability of landing a vehicle in a cross wind. The question naturally arises as to whether the roll control effectiveness requirements of Table X are sufficient for cross-wind landings. The results of a landing approach study (Reference 63) were reviewed. In that in-flight research program, marked increases were noted in roll control power requirements for configurations with high $|\phi/\beta|_d$ and low ω_{η_d} when the aircraft was flown in turbulence with a 25 to 30 knot cross wind component as compared to a 10 to 15 knot cross wind component. Since paragraph 3.3.7 specified that the operational vehicles have the capability of being landed in a 30 knot cross wind, the results in Reference 63 are meaningful to re-entry vehicles as well as to airplanes. An examination of the data indicated that the roll control effectiveness for Class IV vehicles shown in Table X is adequate to meet roll control power requirements for Level 1 with a 25 to 30 knot cross wind. The roll control effectiveness for Class III vehicles appear, however, to be inadequate.

Another in-flight evaluation (Reference 64) was recently published in which a four engine jet transport was flown during the approach and landing with different amounts of lateral control power available to the pilot. Unfortunately, the research was performed in smooth air and no approaches were made in cross wind conditions. The general applicability of the data to Class III operational vehicles flying in turbulence and cross wind conditions is questionable.

The results of Reference 63 appear to indicate that Flight Phase Category C roll control effectiveness requirements in Table X may be inadequate in 30 knot cross winds with turbulence and high dihedral, especially for Class III vehicles. But since the roll control effectiveness requirements of 3.3.4 are not primarily turbulence and cross wind requirements it was decided not to increase the roll control effectiveness figures of Table X. High dihedral effects in the landing approach are converted by 3.3.6.3.2 and cross wind requirements are converted by 3.3.7.1. Roll control must also be adequate to balance the vehicle with the turbulence levels of 3.7.3 and 3.7.4.

All of these factors appear to be reasonable grounds for not reducing the roll control effectiveness requirements for experimental vehicles at this time. The roll control effectiveness of operational and experimental vehicles in Table X are therefore kept the same.

Requirement

3.3.4.1 Roll response to aileron control force

Discussion

The maximum roll response sensitivity denoted by the bank angle achieved in one second per pound of aileron control command is similar to paragraph 3.3.4.1.4 of Reference 2. The purpose of such a requirement is to prevent the lateral response from being so high that the pilot has difficulties in precision of bank angle control. At first, the requirements in this paragraph might seem redundant since 3.3.4.2 specifies a minimum level of lateral forces. However, upon further examination, it is obvious that requirements on minimum aileron control forces alone are not sufficient to prevent the pilot from encountering difficulties in attempting to control bank angle precisely.

The primary difference between the roll response sensitivity requirements for re-entry vehicles and for conventional aircraft is that a requirement has been included for Flight Phase Category B, Level 1. This requirement is much more lenient than for Flight Phase Category A, Level 1 because the maneuvers are gradual and precision tracking is not required as noted in the definition of Flight Phase Category B. It is reasonable to specify a less stringent requirement for Flight Phase Category B than for either Flight Phase Category A or C.

Requirement

3.3.4.2 Aileron control forces

Discussion

The maximum aileron-control forces listed in Table X(include limits for both the operational and experimental vehicles. The requirements for operational vehicles are laid out in a matrix of Flight Phase Categories and Levels consistent with similar groupings in Reference 2. For Flight Phase Categories A and B, Levels 1 and 2 and all Flight Phase Categories, Level 3, the maximum allowable wheel force is twice the maximum stick force. For Flight Phase Category C, Levels 1 and 2, the limiting stick and wheel forces are identical to permit one-handed operation in the landing approach. The limits on the maximum lateral forces for the experimental vehicle in any Flight Phase or Level is simply 35 pounds for a center-stick-controlled vehicle and twice that value for a wheel controller. These forces are considered reasonable and consistent with what a pilot of an experimental vehicle is capable of handling.

The minimum lateral force for each Level is the same as the comparable Level for conventional aircraft.

Requirement

3.3.4.3 Linearity of roll response

Discussion

Although this requirement is qualitative, it is important to handling qualities when precision of lateral control has to be maintained. Lateral nonlinearities that affect the roll response may be due to one or more problems like deadzones, nonlinear force gradients, detents, spoiler lags, etc. As an example, if the nonlinearity is caused by nonlinear force gradients, the problem would be manifested by either an increase or decrease in response of the vehicle with a linear increase in force application. For the case where the response is increased significantly with a linear force increase, the result could be an oversensitiveness to which the pilot has to adjust by matching the force required with the response desired. This operation can be accomplished but may be difficult because of the increased workload. The result may be a degradation in mission accomplishment depending on the specific task and other duties the pilot has to perform simultaneously. Since it is not possible to specify quantitative requirements, pilot evaluations should be made for each Class of vehicle and Flight Phase Category as demonstration of the acceptability of nonlinear roll responses.

Requirement

3.3.4.4 Wheel control throw

Discussion

This paragraph sets limits on the amount of lateral cockpit control for vehicles designed to use a wheel controller. The $\pm 60^\circ$ limits which are reasonable for one-handed operation are the same as established in Reference 3. They were determined from research performed in ground-based and in-flight simulators and reported in Reference 65. The wheel throw limits of ± 80 degrees for completely mechanical systems were included so as not to severely restrict the designer of vehicles with a simple lateral control system.

Requirement

3.3.4.5 Rudder-pedal-induced rolls

Discussion

The first part of this paragraph is directed at re-entry vehicles achieving a minimum roll rate from the use of rudder without any aileron control inputs. The requirement is similar to 3.3.4.5 of Reference 2 and is consistent with the tasks that pilots of re-entry vehicles perform in the lower atmosphere. As when flying airplanes, pilots of re-entry vehicles like to have the capability of raising a wing with rudder, in particular, when they are otherwise preoccupied with navigation functions, etc. It is interesting

that a vehicle which has this characteristic does not necessarily need to have a stable dihedral. The desired rolling moment can also be produced from a vehicle that has a significant rolling moment in the right direction with rudder application or artificially through a rudder-aileron interconnect.

The second half of the requirement is new and is concerned with the problem of generating excessive roll rate from rudder pedal application. Since the majority of re-entry configurations are characterized by high dihedral effect, a limit is needed to keep rolling moments due to rudder from producing excessively large roll rates. Another reason for having an upper bound on rudder-pedal-induced rolls is to preclude the situation in which a large percentage of the available aileron control power is used up in counter-rolling moments. These upsetting moments could be produced inadvertently from inputs to the rudder made by the pilot or caused by a malfunction of the augmentation system. Although no quantitative limits are specified on the maximum allowable roll rate produced from rudder inputs, this new requirement should help in minimizing lateral control handling problems that result from intentional or inadvertent rudder deflections.

Requirement

3.3.5 Directional control characteristics

Discussion

This requirement on directional stability and control characteristics is a general catch-all requirement on balancing yawing moments. As in Reference 2, a qualitative requirement on sensitivity to rudder pedal forces has been included because of the absence of sufficient data that could represent substantiation for a quantitative requirement. However, this requirement has implications on other paragraphs of the specification that have quantitative requirements associated with them. In particular, the latter part of 3.3.4.5 is concerned with the maximum allowable roll rates produced by rudder pedal inputs. Requirements on rudder pedal forces for specific conditions are given in the paragraphs referenced below:

3.3.5.1	(speed change)
3.3.5.1.1	(asymmetric loading)
3.3.5.2	(go-around)
3.3.6, 3.3.6.1	(steady sideslips)
3.3.7, 3.3.7.1, 3.3.7.2	(crosswinds)
3.3.8	(dives)
3.3.9.1, 3.3.9.2	(asymmetric thrust)

Requirements

3.3.5.1 Directional control with speed change

3.3.5.1.1 Directional control with asymmetric loading

Discussion

These paragraphs are quite similar to 3.3.5.1 and 3.3.5.1.1 of MIL-F-8785B(ASG), Reference 2, with the exception that any reference to propeller-driven vehicles is not included. The directional control with speed change requirement places quantitative limits on the rudder pedal forces associated with flight within the Service Flight Envelope. Without retrimming directionally, only reasonable rudder pedal forces are allowed when increasing or decreasing speed from a given trim point. The second requirement is directed at keeping control trim forces low when flying within the Operational Flight Envelope with an asymmetric loading. The primary intent is to keep the rudder pedal forces down to realistic values when flying a vehicle with an asymmetric loading.

The possibility exists that the above requirements, which are valid for both the operational and experimental vehicles, could be relaxed for the experimental vehicle. However, until some experience is accumulated with standard size re-entry vehicles flying various Flight Phases or until detailed information becomes available regarding the specific mission of the experimental vehicle, no attempt will be made to specify the requirement differently for the experimental vehicle.

Requirement

3.3.5.2 Directional control in go-around

Discussion

This requirement is based on the same numbered paragraph in MIL-F-8785B(ASG), Reference 2. The primary difference is the elimination of requirements that are associated with propeller-driven vehicles. The need for a requirement on the directional control in go-around is obvious. Rudder pedal forces greater than the values specified could contribute significantly to the pilot workload during this critical flight condition.

Requirement

3.3.6 Lateral-directional characteristics in steady sideslips

Discussion

This major section of the lateral-directional flying qualities contains requirements on re-entry vehicle characteristics that are manifested from rudder-pedal-induced sideslips. They are directed primarily at the static characteristics of the vehicle, whereas 3.3.2 was directed at the dynamic properties of the vehicle. Some of the important stability derivatives that influence the static characteristics are N_β , L_β , $N_{\dot{\beta}}$, $L_{\dot{\beta}}$, $N_{\dot{\gamma}}$, and $L_{\dot{\gamma}}$. The makeup of the section has been logically separated into three

divisions: yawing moments due to sideslips, side forces due to sideslips, and rolling moments due to sideslips. In addition, a subparagraph, positive effective dihedral, is included under the third division since it relates to the amount of control power and control forces that are necessary to compensate for the rolling moments induced from sideslips.

This requirement is quite similar to 3.3.6. of MIL-F-8785B(ASG), Reference 2. One notable exception is that the maximum sideslip angle which is applicable to these requirements may be specified by the procuring activity. Therefore the allowable sideslip angle may not be defined as in Reference 2 by either full rudder pedal deflection, 250 pounds of rudder pedal force or maximum aileron control or surface deflection. The rationale for including a fourth method of specifying the maximum sideslip angle is in deference to the very high dihedral characteristic inherent in many re-entry vehicle configurations.

It is also noteworthy that the sideslip angle defined by any one of these limits must be attained prior to the vehicle diverging because of some undesirable characteristic like an uncontrollable rolloff. Obviously, a vehicle with such a response does not meet the requirements.

Requirement

3.3.6.1 Yawing moments in steady sideslips

Discussion

Requirements of yawing moments in steady sideslips are specified by establishing requirements on the sense and linearity of gradients of rudder pedal deflection and rudder pedal force with sideslip. These gradients are important to the pilot because if they are linear, then he is able to predict how an increase or decrease of rudder pedal deflection or force will affect the directional response of the vehicle. The primary difference between this requirement and 3.3.6.1 of Reference 2 is the range of sideslip angles in which the linearity of these gradients applies. Because of the inherently high roll-to-sideslip ratio of re-entry vehicles, these vehicles are not expected to be flown at large sideslips. Therefore it is reasonable to specify linearity of rudder pedal deflection and force with sideslip over a smaller range than for conventional aircraft. For the operational vehicle, Flight Phase Categories A and B, Levels 1 and 2, and all Flight Phases of the experimental vehicle, the sideslip range for linearity of the rudder pedal deflection and rudder pedal force has been reduced to 1/3 and 1/2, respectively, of the values specified in Reference 2. However, for Flight Phase Category C of the operational vehicle, the sideslip limits for linearity of the force gradient remains the same and the range for linearity of the deflection gradient is 2/3 the value specified in the requirements for conventional aircraft. The requirements for the operational vehicle in Flight Phase Category C are stricter because the pilot of an operational vehicle has to control yawing moments due to sideslip more precisely over a wider range of sideslip angles since approaches will be made in turbulence and in other

adverse conditions.

If one of the four factors in 3.3.6 that determine the maximum allowable sideslip angle limits the sideslip to less than the angles specified in this paragraph, then the linearity requirements of 3.3.6.1 are waived for sideslip angles beyond the smaller angle.

Meeting the requirements of the sense and linearity of gradients of rudder pedal deflection and rudder pedal force with sideslip will not necessarily assure static directional stability. Paragraphs 3.3.1.1 and 3.3.1.1.1 are also directed at static directional stability. But as mentioned in the discussion of these two paragraphs, basic unaugmented "weathercock" stability is not required. In other words, the Dutch roll natural frequency can be less than zero, with the control surfaces fixed. Another difference between the two sets of requirements is that the re-entry requirement allows a gradient reduction outside the sideslip range of linearity of no more than 50 percent whereas the MIL-F-8785B(ASG) requirement permits a gradient reduction larger in magnitude. The rationale for making the re-entry requirements stricter is a result of the sensitiveness of re-entry vehicles to sideslips because of the high roll-to-sideslip response ratio. A stricter requirement on rudder pedal deflection and force versus sideslip for re-entry vehicles appears to be justified.

Requirement

3.3.6.2 Side forces in steady sideslips

Discussion

This requirement on side forces in steady sideslips, which is similar to the comparable requirement in Reference 2, is directed at the proper relationship of bank angle to sideslip angle. While a variation in bank angle with sideslip is not necessarily required, an increase in left bank angle with right sideslip or right bank angle with left sideslip is not permitted because it can be confusing. However, even though it is possible, a re-entry vehicle is very unlikely to be designed with this characteristic.

Requirement

3.3.6.3 Rolling moments in steady sideslips

Discussion

The rolling moments in steady sideslips requirement is directed at the sense of the aileron control deflection and aileron control force with sideslip angle. In addition, for Levels 1 and 2, 3.3.6.3 requires linearity of aileron control deflection and force with sideslip. The primary intent of the paragraph is to determine the static lateral characteristics (the magnitude of positive effective dihedral) of the vehicle by means normally used by the pilot. Incidentally, these methods are easily measurable and are amenable

to standard flight test techniques. Because of possible control cross-coupling effects, the requirement does not necessarily specify positive effective dihedral.

Linearity of aileron control deflection and force with sideslip is required so the pilot can control the bank angle of the vehicle more precisely than if the variations were not linear.

Requirement

3.3.6.3.1 Exception for go-around

Discussion

This paragraph, which is essentially the same as in Reference 2, waives the rolling moments in steady sideslips requirements for Flight Phase Category C when a go-around is made. Thus the sense of the gradients of aileron-control deflection and aileron-control force with sideslip angle may be opposite to the way they are specified in 3.3.6.3. It is doubtful that a re-entry vehicle will ever have to use the exception, but since it may be possible, this constitutes sufficient justification for including such an exception.

The allowable aileron-control force of 10 pounds is not a function of controller type because one-handed operation is assumed during the go-around maneuver. The requirement that 50 percent of roll control power be available to the pilot is included to provide a control margin so the pilot can cope with disturbances during a critical low-altitude flight condition.

Requirement

3.3.6.3.2 Positive effective dihedral limit

Discussion

This paragraph establishes limits on positive effective dihedral by specifying both the amount of roll control power and the aileron control force required to compensate for the rolling moments generated from the sideslip angles that are experienced throughout the Service Flight Envelope. The requirement, although similar to 3.3.6.3.2 of Reference 2, differs from it in two important aspects. First, requirements are specified for the operational vehicle and less demanding ones for the experimental vehicle. Secondly, the Level 1 requirements for the operational vehicle are approximately 25 percent more stringent than the Level 1 requirements in Reference 2. The rationale for changing the requirement is that since re-entry vehicles generally have a high roll-to-sideslip ratio, it is reasonable that more roll control power margin should be available to take care of the large rolling moments that might occur. Furthermore, MIL-F-83300 (Reference 62) specified that for Level 1, positive effective dihedral should never be so great that 50 percent of the roll control power available to the pilot and no more than 7.5 pounds of aileron control force should be required for the sideslips expected in service employment. This requirement for V/STOL aircraft is identical to the initial parts of 3.3.6.3.2

for a re-entry vehicle with a stick controller.

The primary reason for setting limits on the amount of positive effective dihedral is the concern that large amounts of the available lateral control power will be needed to check the response of the vehicle due to turbulence. Another reason is because substantial aileron control power will be required when the vehicle is flying in crosswind conditions. This fact is particularly valid if the pilot chooses to employ the standard slip method (upwind wing down and opposite rudder to hold straight flight) in the flare and during touchdown.

Requirement

3.3.7 Lateral-directional control in crosswinds

Discussion

The lateral-directional control in crosswinds requirement for the operational vehicle is the same as the Class III and Class IV requirement in MIL-F-8785B(ASG), Reference 2. The sole difference between that requirement and the one for the experimental vehicle is the velocity of the crosswind component. Since the experimental vehicle will be flown under the most favorable atmospheric conditions, it is reasonable that the velocity of the maximum crosswind be set at a reduced level. As rationale for establishing the 90-degree crosswind component for the experimental vehicle, information was obtained about the operation procedure for the present generation of research lifting body vehicles. An example of some of the highly restricted ground rules is one that would not permit a vehicle to be launched if the wind on the lakebed exceeded 15 knots in any direction or a 10 knot crosswind component to the proposed landing site. In accordance with these restrictions, the crosswind component for the experimental vehicle is set at 10 knots for Levels 1 and 2 and zero for Level 3.

Requirement

3.3.7.1 Final approach in crosswinds

Discussion

This requirement establishes limits on rudder- and aileron-control power necessary to fly the final approach in the crosswinds of 3.3.7. It is directed also at the magnitude of the rudder pedal force that produces the sideslip needed to fly in crosswinds and the aileron control forces that compensate for the rolling moments generated from the sideslip. Requirements are specified for the operational vehicle and more lenient ones are specified for the experimental vehicle. The requirements for the operational vehicle are significantly different from the requirements of 3.3.7.1 in Reference 2. For Level 1, the allowable aileron control power available to the pilot and the maximum aileron control force are approximately 25 percent less than the values in Reference 2. Similarly, the Level 2 limits are stricter than the

corresponding requirements for conventional aircraft. These maximums for both Levels are consistent with the specified magnitudes in 3.3.6.3.2, Positive effective dihedral limit. The rationale for making the changes is written in the discussion of 3.3.6.3.2. Briefly, the reason is the high $|\phi/\beta|_d$, roll-to-sideslip response ratio of re-entry vehicles. This characteristic demands considerable control power to check the reaction of the vehicle when it is flown in crosswind conditions. Therefore, 50 percent of the roll control power available to the pilot is specified for Level 1 instead of 75 percent and 75 percent is required for Level 2. Likewise, the reduction in the allowable aileron control force from 10 pounds to 7.5 pounds for Level 1 and from 20 pounds to 10 pounds for Level 2 is to partly account for the high sensitivity in roll because of the high $|\phi/\beta|_d$ ratio.

For the experimental vehicle, the maximum sideslip is 50 percent of the value for the operational vehicle because, as discussed in the rationale of 3.3.7, the experimental vehicle will be flown only under the most favorable atmospheric conditions with a very low crosswind component. Also, in accordance with the reduction in sideslip, it is reasonable that the requirements on aileron control power and aileron control force be less strict than the comparable requirements for the operational vehicle.

Requirement

3.3.7.2 Takeoff run and landing rollout in crosswinds

Discussion

The takeoff run and landing rollout in crosswinds paragraph is similar to 3.3.7.2 for conventional aircraft, Reference 2. It requires that rudder- and aileron-control power be sufficient to maintain a straight path on the landing surface with the cockpit control forces not exceeding the values in the lateral-directional control in crosswinds requirement. This specification has to be met for both the operational and the experimental vehicles up to the crosswind velocities listed in Table XII. This requirement is self-explanatory but is quite important. Some re-entry configurations that are satisfactory under other critical flight conditions may not be acceptable on the runway in the initial portion of a conventional takeoff or the final stage after touchdown.

Requirement

3.3.7.2.1 Cold- and wet-weather operation

Discussion

Obviously, this requirement for cold- and wet-weather operation is applicable only to operational vehicles since experimental vehicles will only be landed on dry surfaces. If compliance under these adverse conditions cannot be demonstrated, the minimum speeds for which directional control can keep the vehicles on the runway by use of aerodynamic controls alone are the

same for Class III and Class IV vehicles as the speeds for airplanes of comparable Classes in Reference 2. These speeds are consistent with the landing task for operational re-entry vehicles since they have to be designed to land on the same wet and slippery runways as conventional aircraft.

As mentioned in the MIL-F-8785B(ASG) BUG, Reference 8, some airplanes that have large side areas tend to be blown sideways when there are high cross-wind components along with very slippery runways. This fact is also expected to be true in the design of many re-entry configurations. Under the detrimental weather conditions mentioned above, it will be difficult for re-entry vehicles with large side areas to keep from being blown to one side of the landing surface. Therefore the last part of the requirement that permits an exception for 90-degree crosswinds at which the force tending to blow the vehicle off the runway exceeds the tire-runway frictional force is also valid for re-entry vehicles.

Requirement

3.3.7.3 Taxiing wind speed limits

Discussion

This paragraph is directed at operational vehicles only since experimental vehicles will not be taxied in winds of up to 45 knots. The requirement is self-explanatory since it is rational that it should be possible to taxi a re-entry vehicle at any angle to a 45-knot wind.

Requirement

3.3.8 Lateral-directional control in dives

Discussion

Lateral-directional control in dives applies to powered vehicles and to unpowered vehicles in equilibrium glide flight. Otherwise the requirement is quite similar to 3.3.8 of Reference 2. The main difference is the deletion of any reference to propeller powered vehicles.

Requirement

3.3.9 Lateral-directional control with asymmetric thrust

Discussion

The intent of this paragraph is to require the safe lateral-directional controllability of the vehicle following sudden asymmetric loss of thrust. One minor difference between this requirement and 3.3.9 of Reference 2 is the insertion of the phrase "inability to get an air start". This qualifying remark may be very applicable to those re-entry vehicles that require air-breathing engines for the approach and landing. These engines have to be

started at the proper time in the latter part of the terminal Flight Phase. However, due to the duration of the soak period in space which may be up to a week or longer, the capability of obtaining a good air start and stabilized engine operation is an unknown. Even though the inability to get an air start does not constitute a sudden asymmetric loss of thrust, it still may cause a substantial lateral and directional out-of-trim condition (depending on the location of the nonstartable engine and the total number of engines). Therefore, this addition to the requirement may be as significant to the lateral-directional handling qualities as the controllability following a sudden asymmetric loss of thrust.

Requirement

3.3.9.1 Thrust loss during takeoff run.

Discussion

This paragraph is essentially the same as 3.3.9.1. of MIL-F-8785B (ASG), Reference 2. At first, consideration was given to permitting a larger lateral deviation than 30 feet following thrust loss during the takeoff run. It seems reasonable that a bigger sideward variation be allowed since re-entry vehicles will not normally be making horizontal takeoffs from narrow runways on a routine all-weather basis. However, without further available information or experimental data that could be used to permit a greater departure to either side of the intended path, the requirement remains the same as for conventional aircraft.

As stated in Reference 2, this requirement is essentially a qualitative one because of the many variables that would have to be weighed in formulating a more exact definitive requirement. In spite of the nonquantitative nature of 3.3.9.1, the requirement does fulfill the primary objective of ensuring that, following thrust loss during the takeoff run, the pilot can either safely reject or safely continue the takeoff.

Requirement

3.3.9.2 Thrust loss after takeoff

Discussion

There is no change in the specification of this paragraph and the comparable one in Reference 2 because the re-entry requirement is addressed to the same task as for conventional aircraft. The purpose of this requirement is to ensure that a straight flight path and a safe climb-out can be made following a thrust loss after takeoff. The straight flight path does not have to be parallel to the runway. The use of automatic devices which operate in the event of a thrust failure are permitted as well as banking the vehicle as much as 5 degrees away from the inoperative engine.

Requirement

3.3.9.3 Transient effects

Discussion

Although the requirement on transient effects following a sudden loss of thrust is basically qualitative, it can have an important effect on handling qualities. Due to the inherently high roll-to-sideslip ratio of the Dutch roll mode of many re-entry configurations, the sideslip generated from the sudden asymmetric thrust condition can cause large roll rate and bank angle oscillations. These motions have to be controlled in an expeditious manner so that dangerous conditions are avoided. The type of pilot corrective action used can be significant because unnatural or unusual control inputs may reinforce the oscillations. In addition, if complicated motions are needed to correct for the asymmetry, than longer time delays will have to be assumed. As a guide to defining a representative time delay, the last part of paragraph 3.4.9 is repeated below:

"This time delay should include an interval between the occurrence of the failure and the occurrence of a cue such as acceleration, rate displacement, or sound that will definitely indicate to the pilot that a failure has occurred, plus an additional interval which represents the time required for the pilot to diagnose the situation and initiate corrective action."

From the foregoing, it is reasonable to assume that a time delay of one second may be unrealistically short. As mentioned in the BIUG for conventional aircraft, Reference 8, the time delay depends upon initial pilot alertness, the extent to which he is actively controlling the vehicle, the magnitude and type of pilot cues, etc.

In summary, this requirement which is similar to 3.3.9.3 of Reference 2 is necessarily qualitative because of the many and different variables that have to be considered in specifying a quantitative requirement that is both complete and unambiguous.

Requirement

3.3.9.4 Asymmetric thrust - rudder pedals free

Discussion

This paragraph is written similarly to 3.3.9.4 of Reference 2. It is addressed to the operational vehicle only and its capability of being flown in steady straight flight with rudder pedals free following asymmetric loss of thrust. The requirement is considered fundamentally important since banking the vehicle rather than yawing or sideslipping it is a more instinctive and natural reaction by the pilot after he perceives an asymmetric thrust condition.

Requirement

3.3.9.5 Two engines inoperative

Discussion

This requirement which was new to MIL-F-8785B(ASG), Reference 2, may be very meaningful to re-entry vehicles, especially those that require airbreathing engines for the approach and landing phases. Due to the length of the cold soak period in space, the chances of obtaining reliable "light-offs" of all engines while descending through the atmosphere is at best an unknown factor. If two engines do not start or if one engine does not start and another engine fails later on, it is reasonable to expect that the resulting transient motion can be contained. In addition, it should be possible to maintain straight flight at any speed between the one-engine-out speed for maximum range and the speed for maximum range with two engines inoperative. Also, in the event that two engines fail simultaneously in the climb following a go-around, for example, this paragraph requires that the lateral-directional characteristics be such that the pilot can recover from the asymmetric condition at any speed above the minimum climb speed. This requirement is reasonable and is consistent with a similar specification in the regulations for transport aircraft.

Requirements

3.4 Miscellaneous flying qualities

3.4.1 Approach to dangerous flight conditions

3.4.1.1 Warning and indication

3.4.1.2 Prevention

Discussion

As is true for airplanes, Section 3.4 attempts to cover flying qualities aspects for lifting re-entry vehicles which cannot be classified as primarily longitudinal, lateral-directional, or control-system characteristics. The requirements treated in this section are the same requirements treated for airplanes in MIL-F-8785B(ASG) with some slight modifications. For terminal flight at low supersonic, transonic, and subsonic speeds the requirements are likely to be similar for airplanes and lifting re-entry vehicles. Undoubtedly, additional miscellaneous flying qualities requirements will develop as the missions, Flight Phases, and tasks of lifting re-entry vehicles are more clearly understood. The subject treated is complex and most of the requirements are qualitative in nature.

The requirements on approach to dangerous flight conditions, and warning and prevention of such conditions are applicable to airplanes and lifting re-entry vehicles. In paragraph 3.4.1.2, nuisance operation of prevention devices is allowed for an experimental vehicle.

3.4.2 Stalls

3.4.2.1 Required conditions

3.4.2.2 Stall warning requirements

3.4.2.2.1 Warning speed for stalls at $1 g \cos \theta$ normal to the flight path

3.4.2.2.2 Warning range for accelerated stalls

3.4.2.3 Stall characteristics

3.4.2.4 Stall recovery and prevention

3.4.2.4.1 One-engine-out stalls

Discussion

The importance of stall requirements to lifting re-entry vehicles is open to some question, since for some lifting re-entry vehicles, a clear stall may not be evident, and the maximum angle of attack or minimum speed may be limited by other conditions besides stall. Also presently, some consideration is being given to lifting re-entry vehicles that may be required to operate at angles of attack far beyond stall. An example is a Faget vehicle that re-enters at an angle of attack of approximately 60 degrees. Since some lifting re-entry vehicles are expected to fly and cruise with engines much as airplanes during some Flight Phases, such as the ferry phase, it was decided to retain the stall requirements with the option that they could be waived with the prior approval of the procuring activity.

The stall requirements as stated are the same as those of airplanes with only a few minor modifications. Angle-of-attack warning may be required for certain Flight Phases since it is the angle of attack and not stall as such that indicates an approach to a dangerous flight condition. For unpowered vehicles, stalls will be made in gliding flight with g 's normal to the flight path of $1 g \cos \theta$. Accelerated stalls for unpowered vehicles will be made in gliding turns.

Requirements

3.4.3 Spin recovery

3.4.4 Roll-pitch-yaw coupling

Discussion

It is highly questionable whether any spin demonstration will be required of lifting re-entry vehicles. In cases where spin demonstration is not required, spin recoveries are not likely to be a requirement. Since some lifting re-entry vehicles during particular Flight Phases will fly and cruise

with engines like conventional airplanes, the spin recovery requirement was retained.

It is questionable whether requirements on roll-pitch-yaw coupling should seriously be considered for lifting re-entry vehicles that are not required to perform violent maneuvers or rapid 360 degree rolls. There was considerable doubt by some contractors and government agencies whether lifting re-entry vehicles could ever meet the roll-pitch-yaw coupling requirements for airplanes as they appear in MIL-F-8785B(ASG). Based on these discussions, it was decided to reduce the rolls to 90 degrees.

Requirements

3.4.5 Control harmony

3.4.5.1 Control force coordination

Discussion

The requirements on control harmony and control force coordination are identical to those of airplanes as stated in MIL-F-8785B(ASG). The same arguments apply, and the discussions on this subject in Reference 8 are applicable to lifting re-entry vehicles in terminal flight at low supersonic, transonic, and subsonic speeds.

Requirements

3.4.6 Buffet

3.4.7 Release of stores

3.4.8 Effects of special equipment

3.4.9 Transients following failures

3.4.10 Failures

Discussion

The need for a buffet requirement is obvious as is the requirement on release of stores. These requirements are taken directly from MIL-F-8785B(ASG). Some thought has been given to lifting re-entry vehicles with expendable tanks, etc., which can be considered to be stores.

The requirement of paragraph 3.4.8 was taken from MIL-F-8785B(ASG) with the references to armament delivery, bomb bay doors, and armament pods deleted. Such references are not expected to be applicable to lifting re-entry vehicles.

The requirements on transients following failures and failures are

self-evident. They apply equally well to lifting re-entry vehicles and are taken directly from MIL-F-8785B(ASG).

Requirements

3.5 Characteristics of the primary flight control system

3.5.1 General characteristics

3.5.2 Mechanical characteristics

3.5.2.1 Control centering and breakout forces

3.5.2.2 Cockpit control free play

3.5.2.3 Rate of control displacement

3.5.2.4 Adjustable controls

Discussion

Section 3.5 deals with requirements of the primary flight control system, including the stability augmentation system, as they are related to flying qualities. The requirements presented here, with minor modifications, are essentially the requirements in Section 3.5 of MIL-F-8785B(ASG) for airplanes. For terminal flight in the lower atmosphere at low supersonic, transonic, and subsonic speeds, one would expect the requirements for airplanes and lifting re-entry vehicles to be similar. It is, however, recognized that lifting re-entry vehicles, especially fully operational vehicles, will have more sophisticated flight control systems than airplanes. The control systems will probably be fly-by-wire and the vehicles themselves will be highly augmented to meet all the mission requirements of an operational vehicle. As the design, simulation, and operational experience with these vehicles develops, the requirements on the primary flight control system will be modified and extended.

The requirements on mechanical characteristics, control centering, breakout forces, free play, control displacement rates, and adjustable controls are the same as the requirements for airplanes presented in MIL-F-8785B(ASG). The need for such requirements appears almost obvious. For more details of the rationale of these requirements and the data upon which the requirements are based, one should refer to Reference 8.

Requirements

3.5.3 Dynamic characteristics

3.5.3.1 Control feel

3.5.3.2 Damping

Discussion

The quantitative dynamic characteristics in paragraph 3.5.3 are essentially the same as those for airplanes in MIL-F-8785B(ASG). In the case of lifting re-entry vehicles, the requirements for Category A have been equated to those for Category B rather than Category C Flight Phases. Category A Flight Phases for lifting re-entry vehicles are considerably less demanding than Category A Flight Phases of airplanes.

An additional statement has been added to the requirement that allows alternate methods of defining acceptable dynamic characteristics if such methods can be substantiated with handling qualities data to the satisfaction of the procuring activity. This addition was felt to be necessary because the flight control systems of operational lifting re-entry vehicles will undoubtedly be complex, and there are indications that some or many of these systems may not be adequately covered by the quantitative requirements as stated in MIL-F-8785B(ASG).

The requirements of Table XIV are based almost exclusively on the flight results of Reference 3. In this experiment, the higher-order dynamic effects, a result of the introduction of various kinds of higher-order control systems, could be adequately represented by a time delay or control system phase shift at a representative airplane frequency. It has been suggested, and rightly so, that the effects of various kinds of flight control system dynamics on handling qualities cannot always be adequately represented in terms of phase shift, and some phase shift or delay may be desirable in some cases to attenuate a vehicle that responds abruptly to control inputs. It has also been recently recognized that there should also be requirements or limits on control system lead as well as control system lag. Some of these additional aspects of control system dynamics on handling qualities are discussed in Reference 4.

Suggestions have been made that the effects of complex control systems can be adequately represented by a partitioning of the overall dynamic effects into an "effective" control system and an "effective" airframe. It has also been suggested that the amount of phase shift should be a function of the "effective" bandwidth of the airplane. But requirements that have been developed based on these suggestions using particular data, are often not supported by new data, such as the data of Reference 4. At present, no adequate procedure exists for establishing handling qualities requirements for the large variety of flight control systems that may be used in airplanes or lifting re-entry vehicles.

The requirements on control feel and control damping are identical to those in MIL-F-8785B(ASG) for airplanes. The rationale and data to support these requirements are discussed in detail in Reference 8.

Requirements

3.5.4 Augmentation system

3.5.4.1 Performance of augmentation system

3.5.4.2 Saturation of augmentation system

Discussion

The statements on requirements of paragraphs 3.5.4 and 3.5.4.2 are identical to those in MIL-F-8785B(ASG) for airplanes. One should refer to Reference 8 for the rationale and the details upon which the requirements are based.

Paragraph 3.5.4.1 on the performance of augmentation systems has been expanded to include performance degradation due to limit cycle, and coupling due to structural vibration and structural modes. Limit cycles are self-sustaining oscillations in closed-loop systems caused by phase lag introduced through nonlinearities such as hysteresis, "slop", and deadband. Coupling due to structural vibration and structural modes is really structural resonance caused by the augmentation system.

Since re-entry vehicles are likely to operate at high augmentation system gains, there is a danger of limit cycles and structural resonance reaching magnitudes which might cause loss of control by the pilot or structural damage to the vehicle.

NASA FRC at Edwards, California has experienced limit cycle problems with the augmentation systems of the X-15, F-111, and lifting bodies such as the M2-F2, HL-10, and X-24A. Based on this experience, NASA FRC has developed a ground testing technique and criteria for limiting limit cycles and structural resonance to acceptable magnitudes. These have been discussed in some detail in Section III under paragraph 3.2.2.1.3 and this discussion will not be repeated here.

Based on NASA FRC experience with lifting bodies, a design acceptance criterion has been developed as shown on Figure 14 of Section III, paragraph 3.2.2.1.3. These limit cycle criteria are stated in terms of amplitude of the limit cycle at the control surface in degrees (elevator, aileron, or rudder). Limit cycle amplitudes have been defined that are acceptable, marginal, unacceptable, and destructive.

Reference 38 has shown that the magnitude of the limit cycle is related to the total loop gain of the augmentation system. As this gain increases, the phase lag in the control system increases until the "knee" in the limit cycle versus loop gain plot is reached. At this point, the phase lag begins to exceed 180 degrees and the system becomes unstable. Reference 38 states that based on NASA FRC experience, the amplitude of the control surface limit cycle is a good indicator of the proximity of the limit cycle to the crossover point.

As discussed in Section III (paragraph 3.2.2.1.3), performance degrada-

tion due to the limit cycle amplitudes quoted represents degradation in the performance of the flight control system that can lead to such things as structural damage long before the limit cycle levels are sufficiently high to result in a significant degradation in handling qualities.

Based on the data in Reference 39, there is also some question as to whether the control surface limit cycle steady-state amplitudes postulated as limit cycle criteria are truly indicative of the proximity of the limit cycle to the crossover point, and the tendencies of the limit cycle to instability. It is clear that additional work will be required before quantitative limit cycle criteria and requirements can be developed, i.e., requirements related to handling qualities and flight control system design. These limitations in no way detract from the extreme usefulness of reports such as References 38 and 66 in the analysis and design of flight control systems from the standpoint of limit cycle and structural resonance.

Requirements

3.5.5 Failures

3.5.5.1 Failure transients

3.5.5.2 Trim changes due to failures

3.5.6 Transfer to alternate control modes

3.5.6.1 Transients

3.5.6.2 Trim changes

Discussion

The requirements on failures and failure transients, are the same as those for airplanes presented in MIL-F-8785B(ASG), with one exception. The Level 1 requirement for Level 1 failure transients has been relaxed from 0.05 g's to 0.1 g's. The 0.05 g's would be hardly noticed and it is felt to be too stringent for both airplanes and lifting re-entry vehicles. Discussions with contractors and government agencies also generally indicate agreement with a relaxation in the Level 1 requirement.

The requirements on transfer to alternate control modes, transients, and trim changes follow the requirements in MIL-F-8785B(ASG) and require no further discussion here.

Requirements

3.6 Characteristics of secondary control systems

3.6.1 Trim system

3.6.1.1 Trim for asymmetric thrust

3.6.1.2 Rate of trim operation

3.6.1.3 Stalling of trim systems

3.5.1.4 Trim system irreversibility

Discussion

Section 3.6 is concerned with the requirements of secondary control systems as they relate to flying qualities of lifting re-entry vehicles. The requirements presented here are essentially the requirements for airplanes as they appear in MIL-F-8785B(ASG). The requirements on speed and flight path control devices (Section 3.6.2) have been expanded to require an auxiliary drag device for an unpowered lifting re-entry vehicle in the landing approach.

It is recognized that secondary control systems of fully operational lifting re-entry vehicles will undoubtedly be more sophisticated and differ in many details from the secondary control systems of conventional airplanes. For example, much of the trim system may be completely automatic, at least for some Flight Phases. As information from design, simulation, and actual operational experience becomes available, the requirements on secondary control devices will be revised.

None of the requirements in Sections 3.6.1, 3.6.1.1, 3.6.1.2, 3.6.1.3, and 3.6.1.4 have been changed from the requirements in MIL-F-8785B(ASG). Reference 8 explains the need for the requirements and presents the rationale upon which these essentially qualitative requirements are based.

Requirement

3.6.2 Speed and flight-path control devices

Discussion

The intent of this requirement, when applied to airplanes or lifting re-entry vehicles, is to assure that the response time and effectiveness of fore-and-aft controls is adequate to control airspeed and flight path. The requirement for airplanes is basically qualitative in nature.

The importance of this requirement has been especially evident to pilots and flight test engineers at Edwards Air Force Base who have been associated with landing unpowered experimental airplanes such as the X-15, and unpowered experimental lifting re-entry configurations such as the M2-F2, HL-10, X-24A, and the M2-F3. For unpowered landings that are to be made routinely with a reasonable degree of precision, NASA and Air Force personnel at Edwards have indicated that an auxiliary drag device is a requirement. Discussions with NASA and Air Force personnel have indicated that, based on their experience, the auxiliary drag device must be capable of doubling the

minimum drag during the landing phase of flight. This experience is the basis for the quantitative requirement for unpowered lifting re-entry vehicles. Since the drag device must be modulated to both increase and decrease speed and flight path angle during the landing approach, its nominal position will be partial extension.

Requirements

3.6.3 Transient and trim changes

3.6.3.1 Pitch trim changes

3.6.4 Auxiliary dive recovery devices

3.6.5 Direct normal-force control

Discussion

The requirements on transients and trim changes, pitch trim changes, auxiliary dive recovery devices, and direct normal-force control are essentially the same as the requirements in MIL-F-8785B(ASG). The discussion in Reference 8 should be consulted for more detailed explanations of the need for these requirements.

An exception to the requirements on pitch trim change conditions, paragraph 3.6.3.1, has been made. The table on pitch trim change conditions referred to in paragraph 3.6.3.1 of MIL-F-8785B(ASG) has been omitted. For lifting re-entry vehicles, it appears that pitch trim change conditions cannot be adequately defined at this time and these trim change conditions are best established by the procuring activity for each specific lifting re-entry vehicle.

Requirements

3.7 Atmospheric disturbances

3.7.1 Use of turbulence models

3.7.2 Turbulence models

3.7.2.1 Continuous random model (von Karman form)

3.7.2.2 Continuous random model (Dryden form)

3.7.2.3 Non-Gaussian models (von Karman and Dryden forms)

3.7.2.4 Discrete model

Discussion

Included in Section 3.7 are the requirements for turbulence models to be used by the contractor in any analysis and simulation of flying qualities to assess the compliance of a lifting re-entry vehicle to flying qualities requirements with atmospheric disturbances. The atmospheric disturbances specified are essentially those for airplanes in MIL-F-8785B(ASG) with modifications to make them more applicable to lifting re-entry vehicles. A detailed discussion of atmospheric disturbances, turbulence models, turbulence levels, and the application of turbulence models in analysis is contained in Reference 8. This discussion, with minor modifications to be noted here, applies equally well to lifting re-entry vehicles.

There is ample evidence to indicate that atmospheric turbulence is a problem of considerable significance to lifting re-entry vehicles. This concern is expressed by lifting body pilots in Reference 35 in a paper entitled, "Pilot Impressions of Lifting Body Vehicles." Reference 60 describes some of the lateral-directional handling qualities problems associated with control of re-entry vehicle configurations in the presence of atmospheric turbulence.

The response and control problems in turbulence of lifting re-entry vehicles are usually associated with several of the characteristics typical of lifting re-entry vehicle configurations. Lifting re-entry vehicles are what can be described as "inertially slender" vehicles. This is a way of saying that the rolling moment of inertia is much smaller than the moments of inertia in yaw and pitch ($I_{xx} \ll I_{yy}$, $I_{xx} < I_{zz}$). "Inertially slender" aircraft display more pronounced roll responses, especially roll responses due to sideslip (L'_β). The roll response due to sideslip is roughly proportional to L'_β at all gust frequencies. At high frequencies, L'_β is the primary roll response parameter, but at low frequencies, the response is also inversely proportional to the Dutch roll frequency and the roll mode root. The Dutch roll damping ratio determines the roll amplification at the Dutch roll frequency. When the Dutch roll damping is low, the roll response at the Dutch roll frequency will predominate and under these conditions, a good indication of the roll response is provided by the bank angle to sideslip ratio, $|\phi/\beta|$. The bank angle response to sideslip disturbance is, of course, dependent also on the power spectral density of the disturbance as well as the airplane transfer function. The initial roll acceleration and the roll angles that result from a sharp edged gust can also be relatively large because of the relatively small I_{xx} and the low roll damping. References 65 and 66 describe some of the control and gust response problems of inertially slender aircraft. The importance of the frequency response of the vehicle in roll for sideslip gust inputs is discussed in some detail in Reference 68.

The turbulence velocity field is generally assumed to be a zero-mean Gaussian random process. Although there is ample evidence to indicate that the Gaussian assumption is not strictly valid, this assumption is used because of the simplicity it affords in mathematical analysis and simulation. Filtered Gaussian noise does not produce a sufficient number of extreme gusts or "spikes" and the natural "patchiness" which is evident in some

turbulence records. This is one reason that the Gaussian continuous random turbulence model is supplemented with a discrete model in MIL-F-8785B(ASB).

In addition to a discrete model, a continuous non-Gaussian turbulence representation is desirable and will provide more realistic sudden intense gusts due to "patchy" turbulence which can occur occasionally. This kind of turbulence could lead to severe roll control problems for lifting re-entry vehicles in view of their unique lateral-directional characteristics. A non-Gaussian turbulence representation may be especially important in the simulation of side gusts, β_g . Allowing for non-Gaussian models for turbulence representation, at the discretion of the procuring activity, is advisable for lifting re-entry vehicles.

Reeves (Reference 67) has recently investigated the non-Gaussian character of low altitude atmospheric turbulence and an interesting method for simulating atmospheric turbulence velocity components that have non-Gaussian probability density functions. His work was directed toward the goal of accounting better for the natural patchiness of turbulence which leads to quiescent periods and periods of varying turbulence intensity. He replaces the Gaussian probability density function with one that is a modified Bessel function of the second kind with order zero (Figure 34). The Bessel function probability density function yields a greater probability for near-zero velocity fluctuations and a greater probability for large velocity fluctuations (Figure 35).

Reeves' particular simulation method employed spectra having ω^{-2} high frequency asymptotic forms (Dryden spectra). Reeves recommends using the Dryden spectral forms since they are spectrally factorable and permit the use of exactly fitting linear filters. For lifting re-entry vehicles, both von Karman and Dryden spectral forms are allowed for non-Gaussian models as well as the random models. Also, Reeves' development was directed more toward low-altitude turbulence, but certain evidence is available to indicate that high-altitude turbulence is also non-Gaussian.

Requirements

3.7.3 Scales and intensities (clear air turbulence)

3.7.3.1 Clear air turbulence (von Karman scales)

3.7.3.2 Clear air turbulence (Dryden scales)

3.7.4 Scales and intensities (thunderstorm turbulence)

3.7.4.1 Thunderstorm turbulence (von Karman scales)

3.7.4.2 Thunderstorm turbulence (Dryden scales)

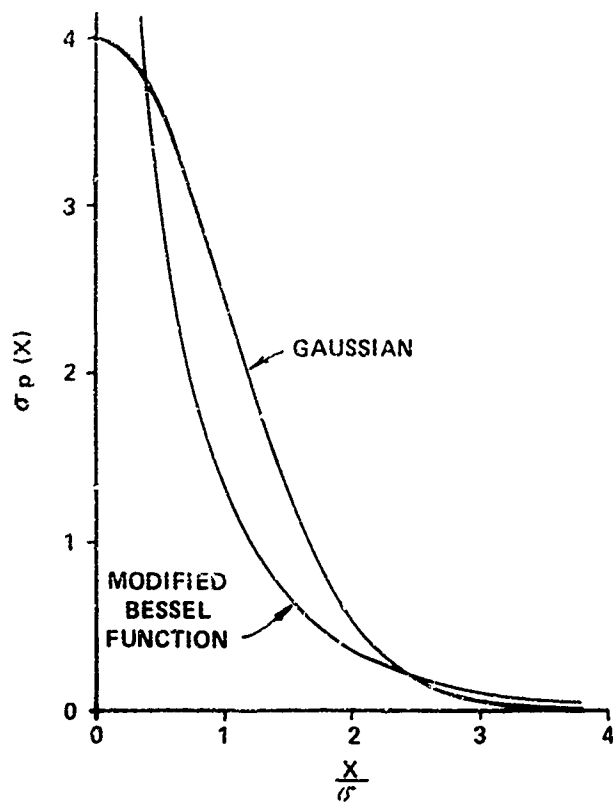
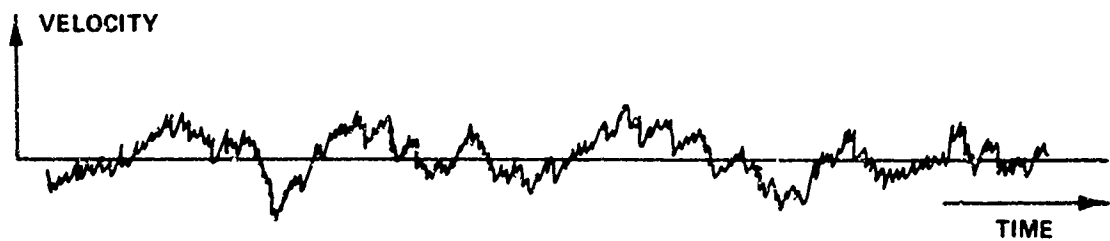
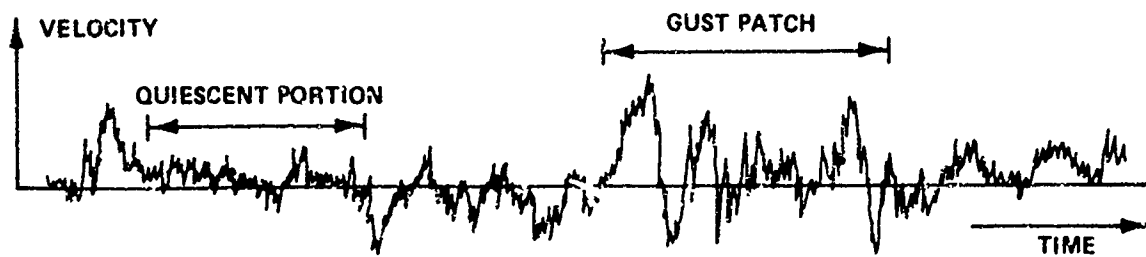


Figure 34 COMPARISON OF PROBABILITY DENSITIES



(a) GAUSSIAN FORM OF TURBULENCE ~ RANDOM



(b) MODIFIED BESSEL FUNCTION FORM OF TURBULENCE

Figure 35 SKETCH OF TURBULENCE FORMS

Discussion

The requirements on the scales and intensities of clear air turbulence for operational lifting re-entry vehicles are the same as those for airplanes as they appear in MIL-F-8785B(ASG). The root-mean-square intensity can, however, be reduced for experimental vehicles since they are operated under more ideal flight conditions. The degree of reduction cannot be defined quantitatively at this time and the degree of reduction is left to consultation between the contractor and the procuring activity.

The value of σ_{wr} specified as a function of altitude for clear air turbulence (Figure 8), is that rms level of turbulence that can only be equalled or exceeded with a probability of 0.01, i.e., 99% of the time in flight at a given altitude will involve turbulence with an rms level less than σ_{wr} , or flight in air without turbulence. It is also true from Figure 8, that since σ_{wr} is zero above 90,000 feet, 99% of the time in flight above 90,000 feet will be in turbulence-free air.

Obviously, Figure 8 does not mean that no turbulence is present above 90,000 feet, nor does it mean that high turbulence levels cannot occur, but the probability of any level of turbulence is less than 0.01. Since lifting re-entry vehicles will certainly spend more flight time at high altitudes than airplanes, allowing for higher levels of σ_{wr} at altitude may be justifiable for lifting re-entry vehicles and should be considered by the contractor and the procuring activity.

Thunderstorm turbulence is not expected to be a consideration for experimental vehicles because of the more ideal atmospheric conditions under which they will operate.

Requirement

3.7.5 Application of the turbulence models in analysis

Discussion

The requirements for applying turbulence models in analysis are essentially the same for lifting re-entry vehicles and airplanes. The detailed discussion of the requirements in MIL-F-8785B(ASG) is applicable with the additional considerations to be presented here.

Although simplicity in gust simulation is always desirable, this is especially the case for lifting re-entry vehicles if non-Gaussian turbulence models are to be used. The primary consideration for lifting re-entry vehicles is likely to be the lateral-directional response, particularly the roll response which is strongly influenced by the low roll moment of inertia and high roll due to sideslip of lifting re-entry configurations. Of the six gusts β_g , p_g , and r_g produce lateral-directional responses and the side gust $\beta_g = -u_g/V$ is clearly of primary importance. When the span of a lifting re-entry vehicle

is small compared with the predominant vertical gust wavelengths, the effects of p_g , the spanwise gradient of the vertical gust, is also likely to be small. It is also true that the rolling moment due to p_g is small when the unaugmented vehicle roll damping is small. In such cases, it may be justifiable to neglect the second-order input p_g . The yaw gust velocity, r_g , is also a second-order input and its effects can probably be safely neglected for some lifting re-entry configurations.

In the longitudinal case, the head-on gust u_g at altitude can probably be neglected compared to α_g . In the landing approach, however, it may be advisable to include u_g in the simulation. The second-order magnitude input q_g can probably be safely neglected for some lifting re-entry vehicles.

In the simulation of gusts for lifting re-entry vehicles, it may often be adequate to simulate only β_g for lateral-directional motions and α_g for longitudinal motions. It is also probably true that q_g and r_g can be obtained from α_g and β_g simulation with only a small amount of additional complication in equipment. Of course, care must be used in making decisions on simplifications in gust simulation for lifting re-entry vehicles since these simplifications may be strongly configuration dependent. It is left to the contractor to supply justification to the procuring activity for any simplifications in gust simulation for the purpose of investigating vehicle flying qualities.

Since lifting re-entry vehicles will in many cases be highly augmented, it should be emphasized that the turbulence velocities (u_g , w_g , p_g , q_g , r_g) agreed upon will be applied to the unaugmented aerodynamic terms in the vehicle equations of motion and the air sensors used in the augmentation.

Requirements

4 QUALITY ASSURANCE

4.1 Compliance demonstration

4.2 Vehicle States

4.2.1 Weights and moments of inertia

4.2.2 Center-of-gravity positions

4.2.3 Thrust settings

4.3 Design and test conditions

4.3.1 Altitudes

4.3.2 Special conditions

4.4 Interpretation of qualitative requirements

Discussion

The requirements of this specification are intended to apply to those Flight Phases, loadings, external store configurations, and geometric configurations of a lifting re-entry vehicle during terminal flight at low supersonic, transonic, and subsonic speeds. The requirements are also expected to consider the various failure states of the vehicle. Design and flight test experience with lifting re-entry vehicles is extremely limited and it is difficult to specify the critical conditions of the vehicle to meet each of the requirements in the specification. These critical conditions will vary from one lifting re-entry vehicle to another and will also depend on whether the vehicle is to be considered operational or experimental.

The number of design and flight test conditions to be considered must of necessity be extremely limited and the limitations are to a large extent determined by considerations of time and money. Experimental lifting re-entry vehicles are usually low budget, "one of a kind" vehicles. For "low budget" vehicles, a greater degree of reliance on checking compliance to the requirements will be determined by analysis, simulation, and ground tests.

The specific loading and flight conditions to be examined must be established by mutual consultation and agreement between the contractor and procuring activity with a realistic consideration of the many factors involved. The discussion and tables in Reference 8 on Quality Assurance for airplanes may be used as a guide for design and test conditions to be investigated for lifting re-entry vehicles.

Compliance with the requirements will be determined during glide and gliding turns for unpowered vehicles. When speed is to be held constant and varied from one speed to another, indicated airspeed will be used in unpowered gliding flight.

The requirements on vehicle states are essentially those of airplanes as they appear in MIL-F-8785B(ASG). For unpowered vehicles, nominal settings of drag devices shall be established for selected design conditions where vehicle compliance is to be investigated.

It will not be possible to establish design and test conditions for an unpowered vehicle at fixed altitudes. The terminal and nonterminal Flight Phases will be explored at altitudes as they occur during glides and gliding turns during terminal flight to touchdown.

There are special flight conditions that may be unique to lifting re-entry vehicles and may reveal special problems, based on past experience with such vehicles, and should be investigated in flight if possible. These are:

1. Lowest dynamic pressure and lowest Mach number
2. Highest angle of attack
3. Lowest angle of attack

4. Most critical angle-of-attack condition as determined by mutual agreement between the contractor and procuring activity.

During some Flight Phases, a lifting re-entry vehicle will be required to operate under low dynamic pressure conditions, that is, dynamic pressures lower than those required to sustain the vehicle in level flight. This will be true even within the limitations of this specification which is expected to apply during terminal flight at low supersonic, transonic, and subsonic speeds. Such conditions may be critical from the standpoint of meeting handling qualities requirements and should be considered.

The dynamic characteristics and handling qualities of lifting re-entry vehicles can be strong functions of angle of attack. Based on past experience with some lifting re-entry configurations, this is especially true of lateral-directional characteristics. In fact, flight envelopes for such vehicles are often limited by angles of attack above and below which the handling qualities of the vehicle become unacceptable. It is therefore advisable to check both a high, low, and critical angle of attack region for compliance with the requirements.

Because of the very limited handling qualities data on lifting re-entry vehicles, it is more true of this specification than MIL-F-8785B(ASG) that many of the requirements have been stated in a qualitative way to allow latitude in establishing requirements based on consultation and agreement between the contractor and procuring activity. Final determination of compliance with the requirements will be made by the procuring activity.

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